Deployment-to-dwell metrics and supply-based force sustainment

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Abstract

Purpose – In the present fast-paced and globalized age of war, special operations forces have a comparative advantage over conventional forces because of their small, highly-skilled units. Largely because of these characteristics, special operations forces spend a disproportionate amount of time deployed. The amount of time spent deployed affects service member's quality of life and their level of preparedness for the full spectrum of military operations. In this paper, the authors ask the following question: How many force packages are required to sustain a deployed force package, while maintaining predetermined combat-readiness and quality-of-life standards?

Design/methodology/approach – The authors begin by developing standardized deployment-to-dwell metrics to assess the effects of deployments on service members' quality of life and combat readiness. Next, they model deployment cycles using continuous time Markov chains and derive closed-form equations that relate the amount of time spent deployed versus at home station, rotation length, transition time and the total force size.

Findings – The expressions yield the total force size required to sustain a deployed capability.

Originality/value – Finally, the authors apply the method to the US Air Force Special Operations Command. This research has important implications for the force-structure logistics of any military force.

Keywords Readiness, Continuous time Markov chains (CTMC), Deployment-to-dwell (D2D), Force sustainment, Personnel tempo (PERSTEMPO), Special operations forces (SOF)

Paper type Research paper

1. Introduction

When embarking upon any long-term endeavor, it is important to count or at least estimate the cost necessary to ensure completion. The trouble with counting the cost of wars is that the path to "completion" is often fraught with unknowns. Furthermore, the business of war itself is constantly changing (Votel *et al.*, 2016). Therefore, warfighters and planners must do their best, despite all the unknowns, to ensure the provided military capability is sustainable with the resources on hand.

Special operations forces (SOFs) are uniquely capable to adapt to the changing rigors of war. SOFs are small highly skilled units designed to respond quickly to emerging crises in any part of the world, but they are not designed to conduct a major combat operation without conventional forces (Bucci, 2015; Spulak, 2007). As evidenced by recent global conflicts, SOF use has increased, perhaps to the detriment of their future use (Hennigan,

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2017; Robinson, 2013; Watson, 2017). Employing SOF in a manner that puts production capacity in peril leads to decreasing capability (JP3-05, 2014). Logically, identifying and studying examples of decreasing capability can help reduce the risk of improper employment. Additionally, depleting capability negatively impacts members' combat readiness and quality of life (Losey, 2017b; Woody, 2017).

For the purposes of this paper, an individual's "quality of life" is based on a multitude of factors including mental, physical, social and spiritual well-being. Combat readiness and quality of life are related because physical and mental well-being affect ability to deploy, in addition to job-related competencies and regular training (Tucker *et al.*, 2005; Rounds, 2010; Szivak and Kraemer, 2015). Consequently, training, deployment and recovery compose the readiness cycle.

One way to measure the readiness and quality of life of an individual or an organization is to look at deployment-to-dwell (D2D) ratios (Dabkowski *et al.*, 2009; Langstroth, 2013; MacGregor *et al.*, 2014; Trautmann *et al.*, 2015). A D2D ratio is the amount of time an individual (or group) is operationally deployed to the time the individual (or group) is not deployed (PM 15-37, 2016). D2D ratios are typically normalized to the length of a deployment so that they are reported as 1:days in dwell divided by days away on the deployment. The recent necessity to obtain waivers for breaching D2D thresholds, at the US Secretary of Defense (SecDef) level, along with low D2D ratios are possible indications of SOF's depleting readiness capacity (Losey, 2017a). These occurrences motivate the overarching research question: How many force packages are needed to sustain a deployed force package, while maintaining predetermined combat-readiness and quality-of-life standards?

As early as May 2005, in guidance on Global Force Management, the SecDef expressed concerns about US military forces' operations tempos and their impacts on the troops (SecDef, 2007; USD, 2005; Chamberlain *et al.*, 2005). In this context, operations tempo refers to how often an individual is away from home because of combat-related deployments or temporary duties. Later, SecDef (2007) established two metrics to measure an individual's operations tempo: personnel tempo and D2D. Personnel tempo measures an individual's operations tempo based on total days away from home station for any duty-related purpose, whereas D2D measures an individual's operations tempo based solely on combat-related deployments. An operational deployment begins when a member departs his or her home station, or en route training location, to meet a SecDef-approved operational requirement (PM 15-37, 2016). An operational deployment ends when the individual arrives back at his or her home station (PM 15-37, 2016). The SecDef imposed restrictions on force supply, for both active and reserve forces, by establishing both personnel tempo and D2D goals and limitations (SecDef, 2007). As originally stated, "the planning objective for the Active Force remains one year deployed to two years at home station" (i.e. 1:2 D2D). The SecDef directive also required that members maintain D2D ratios above 1:1. Though this policy was set nearly 10 years ago because of insatiable demand and little to no enforcement of supply restrictions, SOFs have operated at close to 1:1 D2D ratios (Copp, 2018; Losey, 2018).

There are many debates on the scope of SOF's roles and responsibilities (Robinson, 2013). SOFs are faster and more flexible than conventional forces, and SOFs have the skills to address almost any mission. However, it is important to realize that the very characteristic that gives SOF the ability to do what SOF does is the very thing that limits how much they can do: their small size. Many SOF capabilities worldwide are "low density high demand" or, in other words, they are limited assets or forces with unique mission capabilities stressed by continual high requirements for their capabilities. The reality is that as a low-density high-demand force, SOF cannot do everything demanded because their resources are limited.

Therefore, it is in the best interest of the organization to objectively determine the resources that are needed to sustain enduring deployment requirements.

In a resource-constrained environment, protecting production capacity is paramount. In this context, protecting production capacity means producing a sustainable capability by ensuring the availability of training, resources and equipment. Arguably, the most valuable resource is personnel. To protect production capacity in this environment, with less than 100 per cent manning, policies must be put in place to sustain supply. Even with manning at 100 per cent, there can still be readiness problems, especially in the context of insatiable demand. Typically, SOF responds to increasing demands by increasing the quantity supplied. For instance, for US SOF, it is okay to break the SecDef mandate to maintain a D2D of at least 1:1 so long as those breaking the mandate are volunteers and have approval from the first flag officer in their chain of command (PM 14-07, 2014). As a result, supply has increased with demand. An illustration of this paradigm, commonly known as perfectly elastic supply in economics, is provided in Figure 1(a).

In general, if supply exceeds demand and there are no other limiting factors in the system, the number of transactions in the system are limited by the demand. Conversely, a system with insatiable demand, but constrained supply, is limited to the number of transactions possible given the existing supply. In actuality, SOF is ultimately a system

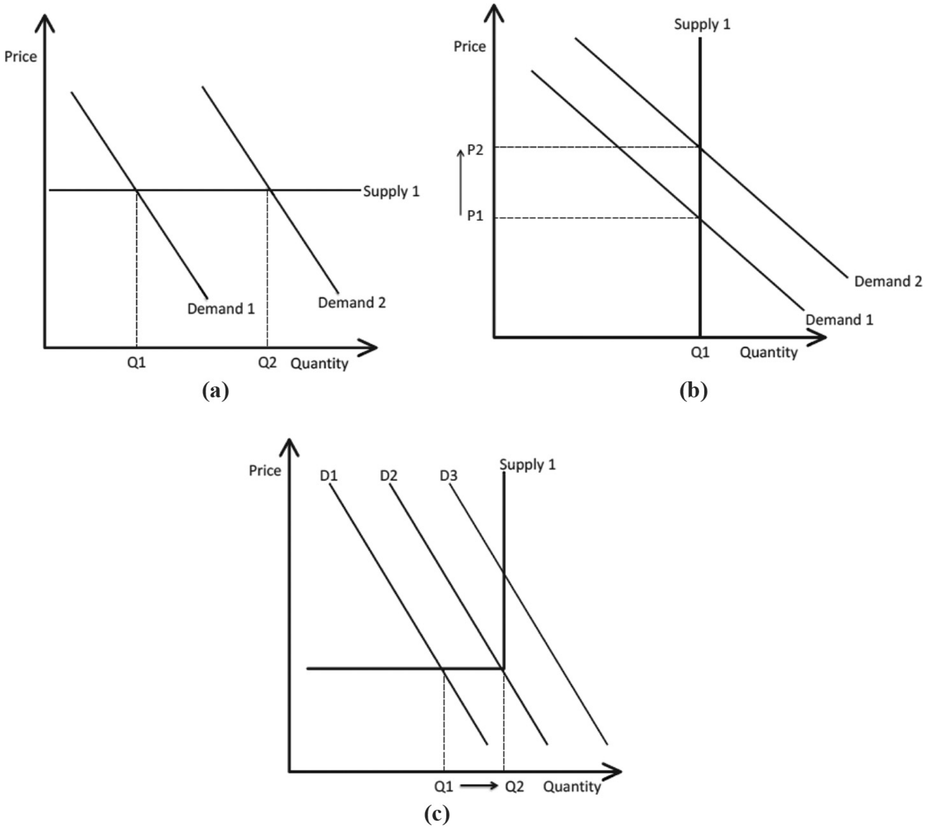

Figure 1.
(a) Perfectly elastic supply; (b) perfectly inelastic supply; and (c) SOF supply

with limited supply under insatiable demands. In economics, this situation is called perfectly inelastic supply and is shown in Figure 1(b). In this case, the price could be viewed as opportunity cost or risk because both increase as demand increases, though the quantity supplied remains fixed. To prioritize one operation over another, in the context of limited supply, is to do that operation at the opportunity cost of the other. Additionally, as there is more unfulfilled demand for SOF, risk increases in the field. Structuring the forces in a manner, which protects production capacity, becomes all the more important in a resource-constrained environment because the parties making demands are not necessarily affected by the costs, either in the long or short term. Rather the service members assume the costs as their quality of life and combat readiness are affected. Therefore, to account for supply limitations, the capabilities should be presented as in Figure 1(c). Figure 1(c) demonstrates how capability supply ceilings allow increases in demand to a predetermined point, after which all increases in demand have no effect on the quantity supplied.

This paper presents a supply-based model for determining the required force strength necessary to sustain an enduring war-fighting capability. We model the problem using a continuous time Markov chain (CTMC) and use the chain's limiting behavior to determine steady-state equations for D2D ratios. The equations yield the relationship between the force multiplier (i.e. the number of identical force packages used to sustain one that is deployed), deployment rotation length, transition time and non-availability of forces.

This research is valuable for several reasons. First, it standardizes an objective measurement of readiness by clearly defining D2D. Second, it develops a method that enables a decision-maker to efficiently allocate resources, based on existing supply, while preserving readiness for the long term. Finally, to mathematically justify current and future force employment decisions, this research derives an equation that relates D2D to key deployment planning factors. Our work is unique and fills a gap in the literature because, to our knowledge, we are the first to relate force sustainment to a quality-of-life metric. This work has undeniable applications to and implications for SOF worldwide and military forces in general.

The remainder of this paper is organized as follows: Section 2 provides the necessary background and framework for the problem. Next, Section 3 logically frames and then presents the methodology in general terms. Section 4 applies the method to US Air Force Special Operations Command's (AFSOC's) active duty forces. Following this, Section 5 states the findings and recommendations.

2. Background

Before attempting to answer the overarching research question, it is essential to properly frame the problem. Any attempt to structure forces, whether conventional or SOF, should begin with determining the capability that is needed. Properly sizing and structuring each force package, or all the equipment and personnel associated with a defined military capability, is important for creating measurable capabilities and reasonable expectations.

2.1 The big picture: capability-based force structuring

Figure 2 explains how the force should be built and structured based on supply. Three phases are used to describe the process: building the force, employing or deploying the force and sustaining the force. In each of the phases, answers to the questions shown in the figure need to be determined.

The first step in the process is to determine the capability or capabilities to be provided.

It is important to understand that larger force packages gain maintenance efficiencies. However, the tradeoff for these efficiencies manifests itself in decreased flexibility. Smaller force packages allow for enhanced projection of the capability to more locations. When creating a force package, it is important to make its capability objectively measurable to effectively communicate the capability's readiness.

We assume initiation in the third phase of the process; an appropriately sized force package has been built and employed, and now it is necessary to determine the number of identical force packages required to sustain each one that is deployed long term. To sustain the force package, we must first determine how to quantify force sustainment. Force sustainment is achieved when force packages are used to provide an enduring capability and that all the personnel involved are healthy. We measure personnel health via D2D.

2.2 Measuring and standardizing operations tempo

The D2D metric we develop meets all of the standards listed in Harrison (2014). The D2D metric measures outputs rather than inputs, is linked to strategy, is quantifiable and avoids subjective assessments. D2D metrics can be used in two separate ways to measure either the historical health or the combat capability (or availability) of the force. We focus on the former.

Based on the definitions provided for dwell and an operational deployment (Section 1; PM 15-37, 2016), individual historic D2D ratios can only be computed for individuals with at least two deployments. To be counted, a dwell period must be bookended with an operational deployment return date and an operational deployment departure date. Each individual's historic D2D ratio is based solely on the length of their penultimate operational deployment and the length of the dwell period immediately following it. Of the three individuals shown in Figure 3, a historic D2D ratio can only be computed for X. X's historic D2D ratio of 1:2 is based on their deployment from 1 January to 31 March and their dwell period from 1 April to 30 September. A historic D2D ratio cannot be computed for Y because

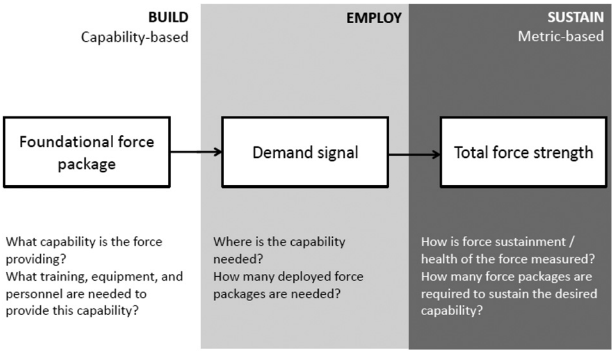

Figure 2.
Force structure overview

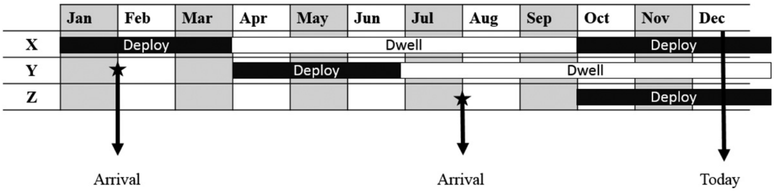

Figure 3.
Historic D2D example

they have not departed on their second deployment and, consequently, their dwell period has not ended. Finally, a historic D2D ratio cannot be computed for Z because they are yet to start their first dwell period.

Though D2D ratios are individual metrics, a group's average historic D2D ratio can be used to answer health-of-the-force questions for different groups of individuals. In an effort to capture the most representative metric, a group's average historic D2D ratio is computed holistically using historic D2D ratios, when they can be computed, from everyone assigned to the group. The holistic average is used to place less emphasis on individual historic D2D ratios that may be considered outliers; an individual with a short deployment followed by a long period of dwell may skew the group's average. To compute the holistic average dwell ratio, one divides the sum of the dwell lengths (in days) for all the members in the group, for which a D2D ratio can be computed, by the deployment lengths (in days) for all the members in the group, or mathematically (for n personnel with valid D2D ratios in a group):

$$\mathit{average\ historic\ dwell} = \frac{\mathit{dwell}_1 + \mathit{dwell}_2 + \ldots + \mathit{dwell}_n}{\mathit{deploy}_1 + \mathit{deploy}_2 + \ldots + \mathit{deploy}_n}.$$

The average historic D2D is then reported as 1: average historic dwell.

An example showing how to compute a group's average historic D2D ratio is given in Table I. Assume that the entire group consists of two members, A and B, with penultimate deployment and last dwell lengths shown. Weighting each deployment equally, the group's average historic D2D ratio is $1{:}\left(\frac{1+3}{1+1}\right) = 1{:}2$. In the holistic average, rather than weighting each individual's D2D ratio equally, the individual ratios are weighted based on their lengths. The group's holistic historic D2D ratio is $1{:}\left(\frac{60+90}{60+30}\right) = 1{:}1.67$. Having developed a standardized way to measure the health of the force, this paper now reviews force sustainment models, both in practice and in the academic literature.

2.3 Force sustainment approaches

Each of the USA's services has a unique way of sustaining their forces via readiness cycles. The intent of each plan is to rotate personnel and equipment in such a way that training, quality of life, maintenance and deployment requirements are all met. Table II describes the methods of the US Air Force, Army, Navy and USSOCOM. As shown in Table II, none of these plans are functioning as perfectly as intended.

2.4 Literature review

More often than not, work in this area views force sustainment from the perspective of readiness measurement or manpower requirements. There is a wide variety of approaches to measuring readiness (Harrison, 2014; Freeman *et al.*, 2014; Barzily *et al.*, 1979; Scales *et al.*, 2011). Our review of the literature on personnel modeling is summarized in Table III. Note that the literature is sorted by method and then by publication date. In an effort to be concise, we only discuss a sample of the literature from each of the methods used and focus

	Deployment length (in days)	Dwell length (in days)	Individual D2D ratio
A	60	60	1:1
B	30	90	1:3

Table I. Example historic D2D calculation

Table II.
Deployment cycle plan comparison

Service/ command	Nomenclature	Directive	Notable characteristics
Air Force	Air Expeditionary Force Cycle	Air Force Instruction 10-244	3-phase, demand-driven cycle. Surge above 12 months may require significant actions to reconstitute the force (AFI10-244, 2002). Disproportionate deployment burdens have been a problem (Losey, 2016)
Army	Army Force Generation	Army Regulation 525-29	3-phase, demand-driven cycle. Will be replaced by Sustainable Readiness Model in fiscal year 2017 because of increased demand in conjunction with decreasing resources (Army Readiness Guidance, 2017)
Navy	Optimized Fleet Response Plan	Office of the Chief of Naval Operations Instruction 3000.15A	4-phase, supply-driven cycle. Maintains the capacity to rapidly increase forward presence as world events dictate and additional funding becomes available (OPNAV Instruction 3000.15A, 2014). Of the fleets converted to OFRP, many have had difficulty maintaining the cycle schedule because of maintenance overrun (GAO, 2016)
USSOCOM	Special Operations Force Generation	USSOCOM Directive 5225-10	3-phase, demand-driven cycle. More of a guideline than a policy because each SOF component must also answer to their respective service (USSOCOM Directive 5225-10, 2013)

on the literature that is closely related to our work. More comprehensive literature reviews and surveys can be found in the studies of Gass (1991), Wang (2005), Guerry and Feyter (2009) and Parlier (2016).

Kinstler *et al.* (2008) use a Markov model to rectify rank imbalances in the Navy Nurse Corps. Filinkov *et al.* (2011) create a software tool to test the personnel sustainability of a land force structure in terms of career progression and operational considerations for the Australian Army. Richmond *et al.* (2012) model the population of ground forces to manage personnel and major system sustainability with Markov techniques for the Australian Army. Zais and Zhang (2016) examine stay or leave decisions in the US Army using a Markov chain model. Mitchell (1993) uses a simulation to estimate the impact on training requirements of force structure decisions for the US Air Force. Pall *et al.* (2007) use a simulation to examine personnel and materiel policies for the Canadian Army. Kim *et al.* (2012) applied a stochastic optimization model to manage the uncertainty of demand and supply for knowledge workers. Durbin and Wright (1967) use linear programing to manage overseas tour lengths for high-demand positions in the US Air Force. Whitney *et al.* (2013) consider the effects of force organization on capability fulfillment using a qualitative methodology for the Australian Army.

While the literature above has important implications, many are impractical for informing the day-to-day decision-making that impacts lives, such as how many force packages to deploy. The effects of military organization decisions on the lives of the people which compose it are important considerations for force management because people's lives are fundamentally entwined with their combat readiness (AFI90-506, 2014). While studies show that deployments have both positive and negative effects on retention, a reoccurring top concern for service members is the amount of time they spend separated from their families (Fricker, 2002; Badger, 2004). Additionally, deployment duration has been

Table III. Academic literature on personnel modeling

Reference	Research question	Method	Application
Mitropoulos (1983)	What metrics best describe members' professional evolution in hierarchical organizations?	Markov model	General
Weigel and Wilcox (1993)	How do high-level personnel planning decisions impact troops at the occupational specialty level?	Markov, network, linear programming and goal-programming models	US Army
Georgiou and Tsantas (2002)	What is the optimal way to minimize cost, in a k-classed hierarchical system, while meeting workforce demand and satisfying government constraints and regulations?	Markov model	European Union/ Workforce
Kinstler *et al.* (2008)	How do different policies impact balance in the rank structure and retention?	Markov model	US Navy Nurse Corps
Filinkov *et al.* (2011)	What force strength is required to meet operational demands, while considering individuals' career progression?	Markov model with hierarchical classes	Australian Army
Richmond *et al.* (2012)	How will personnel and/or major systems populations change over time?	Markov model	Australian Army
Zais (2014)	What are the workforce requirements based on uncertain demand?	Markov model, simulation	U.S Army
Zais and Zhang (2016)	What incentives have the greatest impact on personnel retention?	Markov model, stochastic dynamic programming	US Army
Bender and Isbrandt (1991)	What are the effects of different policy options on career progression?	Discrete event simulation	Canadian Forces
Mitchell (1993)	How many individuals need to be trained annually, for every occupation?	Discrete event simulation	United States Air Force
Zegers and Isbrandt (2006)	What simulation tool most accurately depicts military training and career progression?	Discrete event simulation	Canadian Forces
Pall *et al.* (2007)	What is the most efficient way to provide and sustain qualified units for operational tasks?	Discrete event simulation	Canadian Army
Moorhead and Halbrohr (2010)	What simulation tool best determines the ability of the Canadian Forces to meet the personnel demands of operations?	Discrete event simulation	Canadian Forces
Cao *et al.* (2010)	How can human capital supply chain decisions be improved to drive better business performance with integrated OR models?	Stochastic modeling and optimization	Human Capital Supply Chains
Kim *et al.* (2012)	How does uncertainty of demand for knowledge services as well as the supply of knowledge workers impact recruiting strategy?	Stochastic optimization model	Korean Security Consulting Companies
Durbin and Wright (1967)	How many personnel are needed to meet the requirements associated with rotating personnel between state-side and overseas locations?	Linear programming	United States Air Force
Durso and Donahue (1995)	What are the impacts of personnel management policies on the US Army's enlisted force?	Decision analysis	United States Army
Edwards (1983)	What manpower models exist and to what extent have these been effective in application?	Qualitative assessment	Industry
Whitney *et al.* (2013)	What is the Australian Army's ability to undertake new or existing contingencies?	Qualitative assessment	Australian Army

associated with negative effects on psychological and physical health (Meadows *et al.*, 2017; Mulligan *et al.*, 2012; Szivak and Kraemer, 2015). Our work establishes an easy-to-understand feedback loop for decision-makers which reconnects the costs associated with these effects on the capability demanded. Additionally, this work fills a gap in the existing literature by connecting an objective and mathematically rigorous force sustainment model to a quality-of-life metric.

3. Methodology

For the intents and purposes of this research, force readiness and quality of life are measured solely via historic D2D metrics. We use a 1:2 D2D ratio to logically frame and build the method. After making the necessary logical arguments, we present the resulting formulas in general terms assuming one wishes to maintain a 1:D D2D ratio, as opposed to 1:2.

To perpetually sustain one deployed force package and maintain a 1:2 D2D ratio for all of the associated personnel, at least three force packages are required. The three force packages will rotate through equal periods of deployment, recovery and preparation (Figure 4). As they rotate, the D2D ratios for the personnel assigned to each force package will change as shown. To maintain D2D ratios of 1:2, the preparing force package will not be ready to deploy until all of its associated personnel have stayed in dwell long enough so that their individual D2D ratios are 1:2 or better.

The three-force package model assumes 100 per cent manning and availability in all positions, and instantaneous changeover and transit. In reality, manning shortfalls (in one or multiple crew positions), manning unavailability (in one or multiple positions) and the reality of transit time and responsibility changeover make it so the three-force package model does not provide adequate manpower to maintain 1:2 D2D ratios.

Based on manning shortfalls and non-availability, it may seem reasonable to suggest a force multiplier of four [Figure 5 (left)].

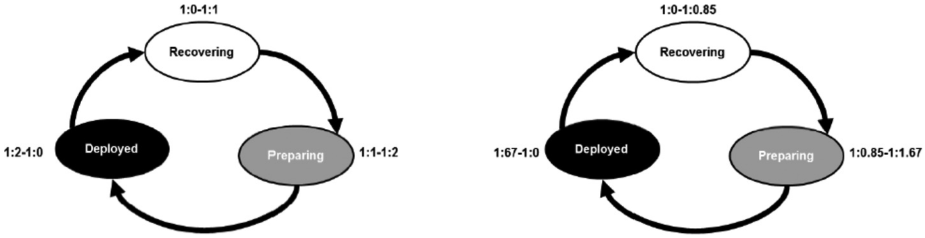

Figure 4.
Three-force package model (left) and three-force package model accounting for changeover and transit time (right)

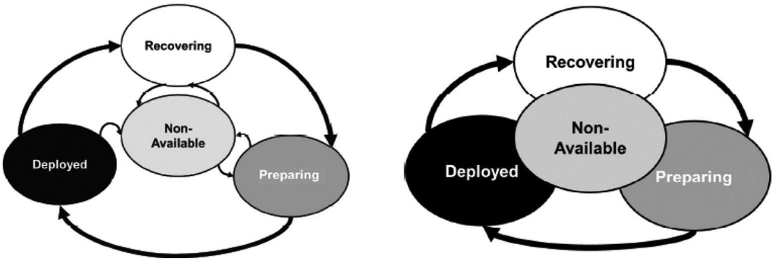

Figure 5.
Four- force package model (left) and four-force package model with overlap (right)

There are several problems with suggesting a force multiplier of four based on the arguments posed thus far. First, the four-force package model compensates for low manning with additional force package-provided billets. Increasing the force multiplier (i.e. adding billets) to compensate for manning shortfalls is nonsensical. The focus should be on filling the empty billets as opposed to asking for more billets.

Second, the idea assumes that all the non-available personnel are entirely separate, or mutually exclusive, from any of the other categories. In reality, non-availability occurs in all the categories; one may become unavailable just prior to their deployment, or they may not be able to accomplish the necessary tasks associated with either the recovery or preparing phases which will create a chain reaction resulting in the individual not deploying on time later in the cycle. Figure 5 (right) illustrates how personnel who are not available can also be in one of the other three categories. Arrows to and from the non-available bucket have been removed to avoid cluttering the diagram.

Figure 5 (right) still does not address the concern about compensating for low manning (i.e. empty billets) with additional force package-provided billets. Consequently, the non-available bucket should only account for the number of non-available personnel of those assigned, as opposed to those authorized. Even so, Figure 5 (right) suggests that the necessary force multiplier is a number between three and four.

Third, because changeover and transit time are still not considered, incorporating them is necessary to ensure that there are no manning gaps. In other words, individuals do not leave the area of responsibility until changeover. The time required for changeover and transit is an important consideration for low-density high-demand assets because, with higher operations tempos, it makes deployment periods longer and dwell periods shorter. For conventional forces, 1:4 D2D rates are more typical so changeover and transit times are effectively negligible.

Figure 4 (right) shows the resulting D2D ratios using the three-force package model and assuming 14 days for transit and changeover with a rotation length of 120 days. In this scenario, the force package's D2D never reaches 1:2. Based on the arguments posed thus far, it seems a force multiplier between three and four is necessary to maintain a 1:2 D2D. However, this conclusion is an impasse; to move forward and better quantify the required force multiplier, a more sophisticated model is necessary.

Therefore, we first model the deployment and dwell periods for the force package using a CTMC and then compute the steady-state probabilities for each state in the chain. Figure 6 depicts the transition diagram. The steady-state probabilities are used to compute historic D2D ratios because they yield the proportion of time a force package is in dwell versus the proportion of time the force package is deployed. With an expression for steady-state probabilities, rearranging reveals the dependence of the force multiplier on rotation length, as well as the amount of changeover and transit time. This CTMC is a birth-and-death process with two states "deployed" (state 0) and "in dwell" (state 1).

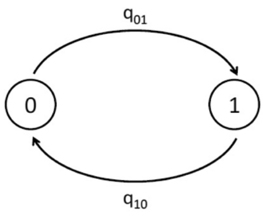

Figure 6.
Transition diagram for one force package

To solve for the steady-state probabilities, the transition rates q_{01} and q_{10} must be found. q_{01} is the rate at which a force package transitions from being deployed to being in dwell. The number of days each force package is deployed is equal to the rotation length, *RL*, plus the fixed number of changeover and transit time, *T*. A force package transitions from deployed to in dwell once every $RL + T$ days. In other words,

$$q_{01} = \frac{1}{RL + T}.$$

Similarly, q_{10} is the rate at which a force package transitions from being in dwell to being deployed. This rate is equivalent to one over the length of time spent in dwell. The length of time spent in dwell equals the rotation length, *RL*, times the number of rotations the force package remains in dwell, minus the fixed number of days spent in changeover and transit, *T*. The number of rotations the force package remains in dwell is equal to the number of force packages that are not deployed (i.e. in dwell) or the force multiplier, *fm*, minus one. Changeover and transit days, *T*, are considered deployment days and, thus, do not count as dwell. Putting all of this together:

$$q_{10} = \frac{1}{RL * (fm - 1) - T}.$$

The steady-state probabilities are derived using the balance equations which, based on the transition rates, are:

$$\pi_0 \left(\frac{1}{RL + T} \right) = \pi_1 \left(\frac{1}{RL * (fm - 1) - T} \right) \tag{1}$$

$$\pi_0 + \pi_1 = 1. \tag{2}$$

The D2D ratio is now simply stated as:

$$\frac{\pi_0}{\pi_1},$$

which can be expressed by rewriting equation (1) as:

$$\frac{\pi_0}{\pi_1} = \frac{RL + T}{RL * (fm - 1) - T}.$$

Normalizing the length of the deployment and writing D2D in the standard format yields:

$$D2D = 1\colon \frac{RL + T}{RL * (fm - 1) - T}.$$

To maintain a D2D ratio of 1:*D*:

$$\frac{RL*(fm-1)-T}{RL+T} \geq D. \tag{3}$$

Finally, to determine how the force multiplier depends on rotation length, as well as changeover and transit time, solve equation (3) for *fm* to obtain:

$$fm \geq (D+1)\left(\frac{RL+T}{RL}\right). \tag{4}$$

Equation (4) yields the force multiplier necessary to maintain long-term 1: *D* D2D ratios based on rotation length, as well as changeover and transit time. Note that the expression:

$$\frac{RL*(fm-1)-T}{RL+T},$$

from equation (3) is useful because it yields a force package's long-term dwell based on rotation length, a given force multiplier, as well as changeover and transit time. Non-availability is still not part of the equation.

To account for non-availability of the assigned manpower, divide the number produced in equation (4) by *A*, where:

$$A = \frac{Number\ Available}{Number\ Assigned}.$$

The final relationship that determines the force multiplier needed to maintain 1: *D* D2D and accounts for rotation length, changeover, transit time and manpower non-availability is:

$$fm \geq \left(\frac{D+1}{A}\right)\left(\frac{RL+T}{RL}\right). \tag{5}$$

4. Application

To show the value of this work, our method is applied to the AFSOC. To begin, we discuss the importance of the holistic D2D average.

Figure 7 depicts individual D2D ratios for members of an AFSOC operations group.

In this particular group, as the histogram on the left shows, approximately 4 per cent of Airmen have dwell rates greater than 19.5 (i.e. D2D ratios less than 1:19.5). The high dwell rates skew the average dwell rate significantly. In this case, all of the high dwell rates are based on deployments that lasted less than 30 days. Often times, because of database and administrative limitations, short trips overseas are coded as deployments when they do not actually meet the definition of an operational deployment. Once the short trips are removed, the mean dwell rate is a more representative metric. However, distinguishing short trips from actual deployments by removing anything that lasts less than 30 days is completely subjective because the 30-day cutoff was chosen arbitrarily. In truth, some deployments last less than 30 days. Typically, when a statistician does not want the measure of central tendency to be impacted by outliers, they will use the median instead of the mean. However, outliers (or short deployments) should not be completely ignored but instead should be weighted appropriately. The holistic average takes short deployments into account but weights them according to their length.

Historically, at AFSOC, based on personnel data from the Military Personnel Data System collected from 2011 through 2014, 85 per cent of authorized billets actually have personnel assigned and 91 per cent of those assigned are available. Therefore, AFSOC tends to have 77 per cent of authorized personnel available. Mathematically:

$$\frac{No.\,Assigned}{No.\,Authorized} = 85\%,\ \frac{No.\,Available}{No.\,Assigned} = 91\%,\ and\ \frac{No.\,Available}{No.\,Authorized} = 77\%.$$

As, historically at AFSOC A = 0.91 and as, for AFSOC's active duty force, the goal is 1:2 D2D ratios, the force multiplier is given as:

$$fm \geq \frac{3}{0.91}\left(\frac{RL+T}{RL}\right).$$

Figure 8 plots the required force multipliers, as a function of rotation length, based on just the combined changeover and transit time (solid line) and based on the combined changeover and transit time plus the non-availability of assigned personnel (dashed line). Note that the required force multiplier decreases, but not linearly, as the rotation length increases. This inverse relationship is expected, as the number of rotations required decreases as the rotation length increases and as every rotation requires a fixed amount of changeover and transit time. As a side note, because each rotation requires a fixed amount of changeover and transit time, as rotation length increases, the total number of days away

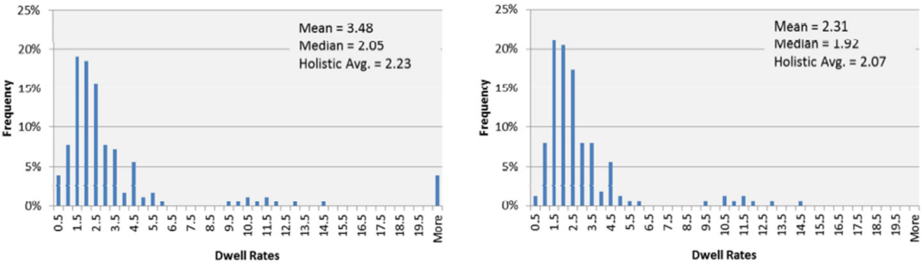

Figure 7.
Left: Dwell rates histogram (all data) and right: Dwell rates histogram (no deployments ≤ 30 days)

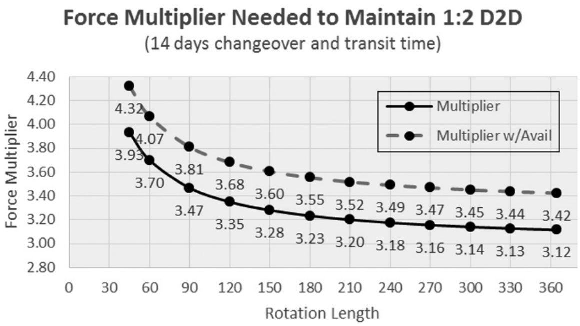

Figure 8.
Force multiplier needed to maintain 1:2 D2D based on rotation length (14 days of changeover and transit time)

decreases. This relationship creates a tradeoff between rotation length and total number of days away.

Based on the math, Figure 8 plots non-integer-valued force multipliers. Fractions of force packages are permissible if compensating for personnel non-availability; however, a fraction of a force package cannot cover a deployment requirement for a full force package. The question becomes "since it is not possible to deploy fractions of people or crews, is it possible to use fractions of force multipliers to determine the correct force strength or force package size?"

The answer is, it depends. If the goal is for personnel to maintain an average D2D of 1:2 over multiple deployments and dwell periods, then the answer is yes. If, however, the goal is to have the manpower necessary so that each dwell period, for each individual, is twice as long as the deployment preceding it, then the answer is no. The latter requires rounding up to the next integer-valued force multiplier. The solid line in Figure 8 shows that rounding up to a force multiplier of four provides the manning necessary to account for changeover, transit time and non-availability for rotations longer than 90 days. Because of rounding up, a force multiplier of four will result in individual and average D2D ratios better than 1:2. The margin by which the D2D ratios are better than 1:2, as shown in Figure 8, increases as rotation length increases.

To determine how sensitive the results in Figure 8 are to changeover and transit time, this paper will now examine how the force multiplier is affected by an increase or decrease in the number of changeover and transit days. Originally the assumption was a total of fourteen days of changeover and transit time, seven days on either end of each rotation. Decreasing the number of changeover and transit days to six (three on either end of each rotation) yields the force multipliers plotted at the bottom of Figure 9. These can be thought of as a lower bound on the force multiplier (i.e. a best-case scenario). On the other hand, increasing the number of changeover and transit days to 20 (ten on either end of each rotation) produces the force multipliers plotted at the top of Figure 9. Ten days of changeover and transit time on either end of each rotation is sufficient, in most cases, to place an upper bound on the force multiplier. Note that, for rotations of 60 days or longer, the force multiplier is generally bounded between three and four.

The key to effectively using the findings of this research is defining what is meant by "maintaining a D2D ratio of 1:*D*." Here, "maintaining" could mean:

- Maintaining an average D2D of 1:*D* over all members in a group.
- Maintaining an average D2D of 1:*D*, for each individual in the group, over all of their individual deployments.
- Maintaining a D2D for each individual in the group, after each deployment.

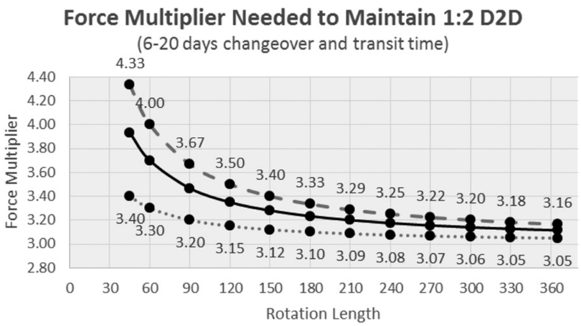

Figure 9. Sensitivity analysis: Force multiplier bounds (6-20 days changeover and transit time)

As this research has shown, the third definition is the most restrictive and, consequently, will require the most manpower and the largest force multiplier. However, the third definition provides service members with the most predictability and, arguably, the best quality of life. If the intent is to satisfy either of the first two definitions, then equation (5) is sufficient to determine the required force multiplier. If, however, the intent is to satisfy the third definition, then the results from equation (5) should be rounded up with consideration for associated risks.

The following example helps to explain some of the finer points of this analysis. Assume the 123rd Special Operations Group has a requirement to deploy an enduring force package of ten individuals for 120-day rotations. Also, assume that there are 14 total days of changeover and transit associated with every rotation, seven days on either end of each rotation. According to Figure 8, not considering availability, and not rounding up to the nearest integer, the 123rd Special Operations Group requires a total of 34 personnel. Figure 10 shows how different groups of personnel will transit and rotate in and out of theater and dwell over a 494-day period (four full rotations plus changeover and transit time).

Personnel are gone for 134 days on each deployment; 120 days for the rotation and 14 days for changeover and transit time. However, as there are not four complete force packages (or groups of ten personnel), dwell periods are neither the same length for each group nor the same length for each individual after each of their deployments. After their first rotation, Personnel 1-6 are in dwell 226 days after their deployment of 134 days and have a D2D ratio of 1:1.69. Personnel 7-10 have a longer dwell period of 346 days and, consequently, a D2D ratio of 1:2.58. Personnel 1-6 have fewer dwell days than Personnel 7-10 because Personnel 1-6 must depart to cover rotation four with Personnel 31-34. The groups of personnel, as listed in the rows, have alternating D2D ratios of 1:1.69 (shown in grey) and 1:2.58 (shown in white). The average D2D ratio, over all personnel or for each individual, over multiple complete cycles, is 1:2.

Two main conclusions can be drawn from this analysis and specifically from the example above:

1. Average 1:2 D2D ratios, over multiple individuals or over multiple deployments for each individual, can be achieved with the force multipliers shown in Figure 8.
2. Individual D2D ratios of 1:2 for each individual and following each deployment cannot be achieved unless the force multipliers shown in Figure 8 are rounded up to four.

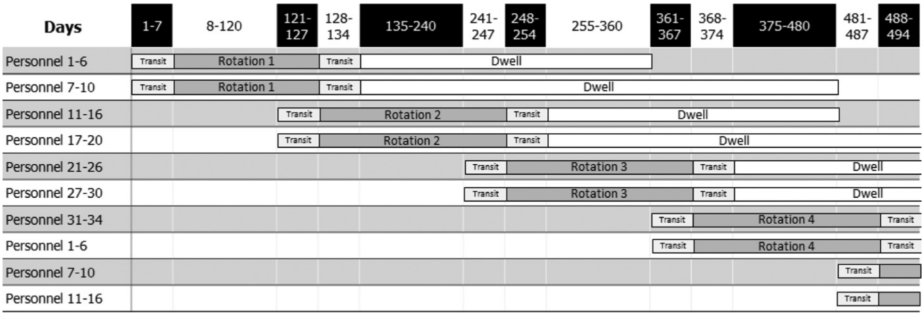

Figure 10.
Example: 123rd special operations group changeover, transit, rotation, and dwell timeline

Additionally, note that the example does not account for non-available personnel and, therefore, is a best-case scenario. When personnel become non-available, variability within the groups shown in Figure 10 is introduced and the required force multiplier becomes more difficult to compute. Because of non-availability, a force multiplier of four does not necessarily guarantee that individuals will not drop below 1:2 D2D. This can happen when someone who is supposed to deploy as part of their normal rotation becomes non-available just prior to their scheduled departure date, and someone else on a separate rotation has to fill in and break their 1:2 D2D. If it is unacceptable for individuals to drop below 1:2 D2D, on such occasions, increasing the force multiplier to a number larger than four may be justified. As the preponderance of AFSOC's rotations are between 90 and 150 days, and as the goal is to generally maintain individual D2D ratios of 1:2 for each deployment, a force multiplier of four is recommended, for every persistently deployed force package.

The case study above highlights a limitation to this research. Many of the results discussed in this section are based on analyses we accomplished for AFSOC and, thus, specific to our application. That said, similar takeaways to those above can be made, for a given organization, if adequate analysis is done up front. At the least, to successfully apply this work, an organization must first determine which of the above definitions is appropriate and study the organization of interest to determine typical deployment lengths and availability of personnel.

5. Conclusion

This work derives closed-form equations for determining the force multiplier required to maintain a specified deploy-to-dwell ratio (i.e. a quality-of-life metric). The equations relate the amount of time spent deployed versus at home station, rotation length, transition time and the total force size, making it possible to analyze the relationships among these factors. Our methodology provides a way to mathematically justify protecting force production capacity to sustain enduring deployments while maintaining predetermined combat-readiness and quality-of-life standards.

The relationships among these factors have important implications for force-structure logistics. Shorter, more frequent force rotations result in greater amounts of time deployed overall because of the transition time incurred for each rotation. Increasing the efficiency of force movements, by making transition times shorter, decreases the overall force size necessary to sustain an enduring deployed capability. Incomplete force packages and unexpected unavailability lead to uneven distributions of D2D ratios within units. Therefore, to improve the equitable distribution of D2D ratios in units, commanders should consider a full force package committed if any part of it is used to meet demand. Objectively calculating the force structure necessary to sustain a deployed capability establishes a definitive supply cutoff, at which the decision maker risks damaging the production capacity of the capability. Additionally, using the simple equations derived above, decision-makers can readily assess force structure logistics decisions in terms of the effects they will have on units' D2D ratios.

Another significant contribution of this work is the development of a standardized method for calculating the D2D metric. While there are current policies governing the management of health of the force via D2D, different interpretations can result in different calculation methods and thus inaccurate comparisons. Standardizing the calculation facilitates objective equitable comparisons and more effective decision-making. Furthermore, using the D2D metric for determining deployed capability sustainment connects force structure decisions with the implications for service members' combat readiness and quality of life, thus associating the service members' cost with the quantity of capability demanded.

Although this research focuses on one aspect of readiness, for a single military organization, over a limited time period, future work could apply the methodology to other military organizations and evaluate the effectiveness of the implementation of this research over time. The method could also be extended to determine the force multiplier based on different readiness or quality-of-life metrics. Additionally, one could analyze the effect of randomly occurring schedule changes on the distribution of D2D throughout the units. Finally, creating a simulation to evaluate the long-term effects of differing types and levels of non-availability on the system, as a whole, provides another opportunity for future work.

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