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Research Report

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Common Shop Stock Lists for the Army's Ground Brigade Combat Teams

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About This Report

This report documents research and analysis conducted as part of the projects entitled *Shop Stock: Purpose, Policy, Strategy, and Demand Planning Standardization* and *Integrated Shop Stock: Implementation and Transition to the Army,* sponsored by Deputy Chief of Staff, G-4, U.S. Army. The purpose of the projects was to implement the Army's concept of common shop stock lists for the Army's armored, infantry and Stryker brigade combat teams (BCTs) and transition the code and metrics to the Army. This report should be of interest to Army logisticians and, more generally, to all logisticians who are involved in the periodic update of spare parts inventories.

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Summary

Analysis of the current shop stock lists (SSLs) across each of the Army's ground BCT types revealed that there was very high variability in the SSLs across units supporting the same equipment, both in terms of breadth and depth. Up to 40 percent of units did not have SSLs (e.g., inventory levels on ten or less parts). The analysis further revealed that where appreciable SSLs were set, the performance was poor (10 percent or less) in terms of filling all parts on high priority workorders both overall and when limited to work orders for critical equipment.

The goal of this research was to dramatically improve performance to better support readiness of critical equipment, while still enabling unit mobility on the battlefield and reducing workload and cost required to conduct periodic SSL updates. Like common authorized stockage lists (CASLs) it was determined that units that support the same equipment would all use the same SSL, referred to as a common SSL (CSSL).

The CSSLs were derived using two key changes. First, the demands across units supporting like equipment were pooled to increase the sample size used to compute inventory levels. Second, the algorithm was changed from a two-step heuristic approach to mathematical optimization. Together these two changes when simulated against actual demands led to increases in shop stock fill rates for maintenance significant parts (MSP) from 5-10 percent for current SSLs to 30-35 percent for the updated CSSLs.

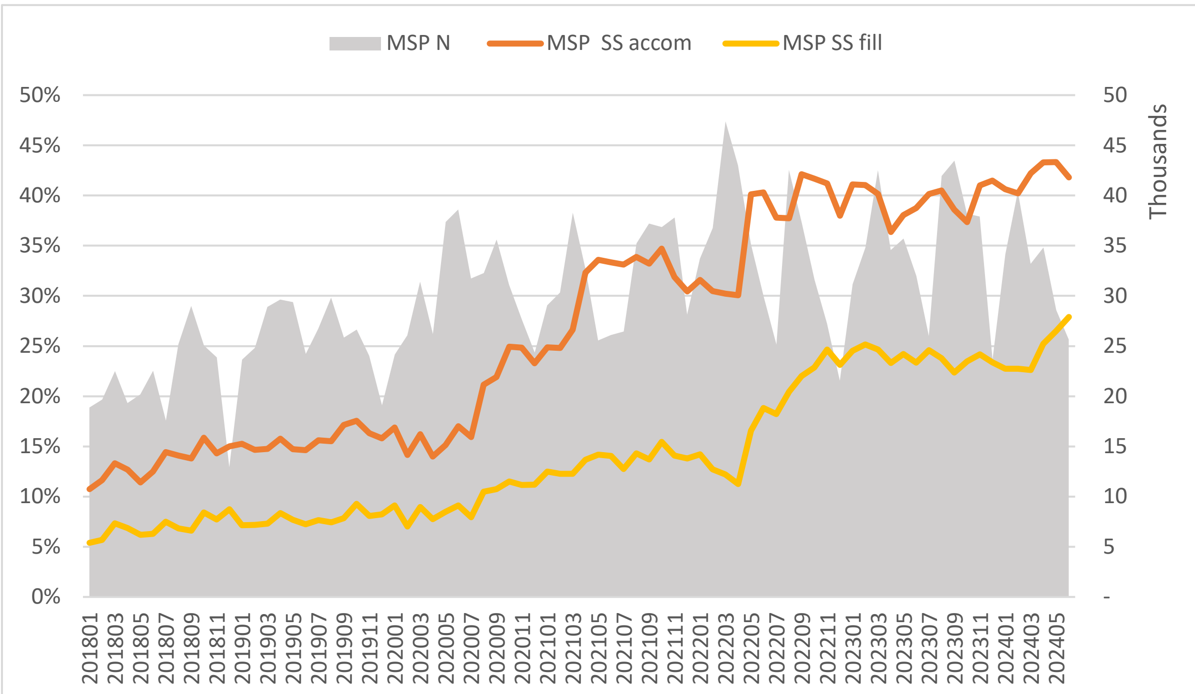
The research team worked with the Army to establish a method using a staging table to load the CSSLs for each of the unit types. Unit personnel then copied the appropriate CSSL inventory levels from the staging table to the unit's storage location (SLOC). Metrics were put in place to track the implementation in terms of posting and activating (turning replenishment on) the CSSLs. The tracking metrics showed it took about a year before 90 percent of the CSSL levels were copied into the unit SLOCs. Furthermore, after a year and a half only about half (50 percent) of the CSSL levels were activated with replenishment turned on.

Actual performance measured in terms of accommodation rate tracked up over time as the CSSLs were copied to the unit SLOCs (see Figure S.1). MSP accommodation rates—a measure of the degree to which CSSLs included the right kind of parts to meet demands—reached levels predicted by the simulation (40 – 45 percent). However, MSP fill rates—a measure of the degree to which CSSLs provided the parts required—reached 25 percent (versus the simulated 30-35 percent), primarily because units were not able to fully fund (i.e., turn replenishment on) for the CSSLs.

The tracking metrics and simulation results suggest that more performance improvements are possible if units can fund (i.e., turn on replenishment) of the CSSLs. If funds are problematic, units could turn on replenishment selectively focusing on the lower cost items. Also, further improvements in part availability can be had at very little additional inventory investment and

storage space by extending the CSSLs to include bench stock items. Further performance improvements may also be possible if unit (plant 2000) inventory accuracy were improved.

Figure S.1. Maintenance Significant Part (MSP) Performance Across All Ground BCTs



SOURCE: RAND Arroyo Center analysis of data from Global Combat Support System—Army (GCSS-A).
NOTES: MSP N = number of MSP part reservations; SS accom = shop stock accommodation; SS fill = shop stock fill rate.

CSSLs were computed for ground BCTs. Because the ground BCTs have many like units (shops that support same/similar equipment), this analysis has shown there is significant benefit to pooling demand and moving from a two-step heuristic process to mathematical programming. However, these benefits are not limited to the Army's ground BCTs. The same concepts and potential benefits would apply to any artillery battalion (BN) or company (CO) unit that maintains an SSL (the more like units, the greater the benefit from pooling the demand histories).

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Chapter 1. Introduction

Motivation and Background

The operational effectiveness of the Army's brigade combat teams (BCTs) depends critically on the readiness of their tactical and combat equipment. When equipment does break down, it is critical that maintainers have access to the repair parts required to restore equipment availability. Given the complexities and difficulties of distributing parts in a combat environment, the fastest way to ensure access to the required parts is to have them on hand in the BCT. When critical parts are not available in the BCT, maintainers must wait for parts, repairs are delayed, and equipment remains unavailable for use in combat operations.

Within the BCT parts are maintained in the BCT's Supply Support Activity (SSA) and within specific maintenance shops. This report deals with setting inventory levels in the maintenance shops, referred to as shop stocks, that enable rapid fix forward repairs.[1] A useful way to think about inventory levels is as the number of parts to be stocked when the shop stock is established before operations take place. In operation, inventory levels are used as parameters in the logic of reordering. In this report, we refer to the inventory level as the safety stock (SS). For the shop stocks the set of parts with inventory levels is referred to as the shop stock list (SSL).

Ensuring that the right repair parts are on the SSL is challenging for many reasons. Maintenance shops support a wide variety of equipment for which there are thousands of different repair parts; the likelihood that any part will fail depends on many factors; and there is extremely limited space to store repair parts because the maintenance shops must be mobile and move with the units that make up the BCT. The U.S. Army's solution to this equipment readiness challenge carefully calculate the SSL, the list of the repair parts and their associated SS, that designated maintenance shops should keep on hand to support the equipment. The SSL is periodically recalculated, reviewed, and updated.

However, until the fielding of Global Combat Support System—Army (GCSS-A) Increment one Wave two, the information system used to manage maintenance and supply activities in the maintenance shop was stored and executed locally on a laptop computer. The algorithm for computing the SSL was part of the information system stored on the laptop and was limited to historical demand data stored on the laptop. Because SSLs were shop specific, the Army faced the burden of periodically calculating and updating SSLs for thousands of shops, including around 500 shops in ground BCTs.

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[1] For a report on setting inventory levels in the BCT's SSA that leveraged a similar approach for setting inventory levels in the BCT's SSA, see Kenneth Girardini, Candice Miller, Rick Eden, *Common Authorized Stockage Lists for the U.S. Army's Brigade Combat Teams*, RAND Corporation, RR-A1376-1, 2023.

Moreover, although shop performance typically improved after each SSL review,[2] there was still considerable variability in performance across shops of the same type and at each BCT over time. Along with uneven performance across shops, there was also concern about the workload associated with executing, reviewing, and implementing an SSL review, particularly while units were about to be or were deployed.[3] Each time the Army reviewed and updated SSLs using the most-recent data, the personnel at the shops also shouldered the workload of reconfiguring their storage locations to accommodate changes to the SSL and redistributing repair parts no longer authorized for stockage.

Research Objective and Approach

Objective

The project's objective was to improve SSLs to (1) achieve higher performance to better support readiness of critical equipment in high-tempo operations, (2) enable unit mobility on the battlefield, and (3) reduce the workload required to reconfigure storage locations and redistribute parts no longer authorized for stockage during periodic updates. Furthermore, shops that support the same equipment would all use the same SSL, referred to as a common SSL (CSSL).

Approach

In response to the desire for CSSLs, RAND researchers leveraged the approach used for computing common authorized stockage lists (CASLs). This approach fundamentally changed how SSLs had been computed in the Army changing both the demand history used in the analysis and the analytic method applied to the demand history.

Rather than using only the demand history of each shop for each CSSL review, the new approach pools the demand history for repair parts across all shops supporting the same equipment (e.g., all armor companies, all mechanized infantry companies, etc.). Pooling demands across shops supporting the same equipment allows the Army to develop CSSLs based on a larger and more-robust demand history that includes more training events and other high-tempo activities. Including the demands from these high–operational tempo (OPTEMPO) events result in a robust CSSL that is more likely to contain the repair parts that shops will need when units deploy.

Historically, the Army has used heuristics to decide whether to add or retain repair parts on each shops SSL and then calculated the depth using separate logic. For the CSSL, the Army has

[2] See AR710-2. SSL reviews were to be conducted every 12 months, but units were often overburdened, and these timelines would often slip.

[3] Further complicating matters, when conversion to GCSS-A occurred in the shops, the maintenance and supply history from Standard Army Maintenance System-Enhanced (SAMS-E) was not imported into GCSS-A due to concerns about cost and data quality. Hence, units were not able to update their SSL until enough consumption history had been built up in GCSS-A.

moved to a mathematical optimization approach, executed using a mixed-integer programming (MIP) algorithm, to simultaneously determine the breadth and depth of parts to maximize the readiness benefit of the CSSL. Using a mathematical optimization approach has several advantages:

- It allows the Army to stress the mission criticality of different types of equipment.
- It allows for storage constraints to ensure the CSSLs are mobile.
- It allows the use of weighting factors to reduce the number of changes to the CSSL and, hence, the transition cost and workload required for CSSL updates.
- Varying weighting factors and storage capacity constraints enables rapid analyses of trade-offs across multiple dimensions (e.g., transition costs to update the CSSL, storage configuration, mobility, and performance).

Organization of This Report

The remainder of this report is organized into four chapters. Chapter 2 provides more detail of the advantages of pooling the demand histories across units in the ground BCTs that support the same equipment and the shift from the two-step heuristic to mathematical optimization. Chapter 3 provides an explanation of the mathematical optimization formulation in nontechnical terms. Chapter 4 provides a description of the Army's initial conversion to CSSLs for the active component armored brigade combat teams (ABCTs), infantry brigade combat teams (IBCTs), and Stryker brigade combat teams (SBCTs) and the improvements in shop stock performance. Chapter 5 provides some concluding thoughts and potential extensions.

Chapter 2. Benefits of Shifting to CSSLs

The Army had several goals for wanting to transition from unique SSLs for each shop to CSSLs for shops supporting the same equipment:

- Further improve SSL performance in providing the repair parts that maintainers need to keep critical equipment ready and available, particularly in high-tempo operations where equipment is more likely to fail and require repair.
- Ensure unit mobility on the battlefield by constraining the amount of storage required for the SSL, thereby limiting the SSL to the repair parts most likely to be needed to maintain readiness of critical equipment.
- Limit the number of changes—referred to as *churn*— during CSSL updates and thereby reduce up-front inventory investment, distribution costs, and workload in the shops.[4]

To achieve these three goals, the shift to CSSLs required making two major changes to the legacy SSL review process (see Table 2.1). One involved changing how the Army used available data on the demand for repair parts. The second involved changing the approach for analyzing the demand data and determining the best mix of parts to stock on the SSL for each type of shop.

This section provides a description of both changes (the rows of Table 2.1) and their advantages (the columns of Table 2.1) in relatively nontechnical terms. Empirical results validating the improvements are given in Chapter 4.

[4] Changes to the CSSL during periodic updates that result in significant SSL performance are beneficial, but large numbers of changes that have very modest impacts on SSL performance is referred to as inventory churn. Churn refers to the addition or deletion of items from the CSSL or the increase or decrease of the depth of an item that remains on the CSSL. Limiting inventory churn brings numerous benefits throughout the supply chain:

- reduces the amount of obligation authority required up front to fund the CSSL update,
- reduces the costs to order, distribute, and receive parts added or increased and the redistribution costs associated with parts that are deleted or decreased,
- reduces the workload required in the shop to reconfigure storage locations.

Table 2.1. The Shift to CSSLs Involved Two Changes with Multiple Benefits

Change to SSL Review Process	Improve SSL Performance	Ensure Unit Mobility	Reduce SSL Churn
Pool part demands from shops of the same type	• More data about demands during high-OTEMPO events are included. • More data are included to inform a robust mix of slow-moving parts.	.	SSL composition is not overly influenced by atypical part demands at a single shop.
Shift from two-step heuristic to mathematical optimization	• Each solution is optimized to deliver the most readiness benefit for available resources. • Emphasis is placed on mission-essential equipment.	Constraints by storage category and location are enforced.	Use of explicit churn weights and trade-off analysis.

Pool Part Demands from Shops with the Same Equipment

The transition to CSSL involved pooling data on demanded repair parts from shops supporting the same equipment. For example, using the demand history across all tank companies supporting the M1A2SEPv2 in a single CSSL review rather than conducting separate SSL reviews using the demand history of each tank company. Pooling demands across shops supporting the same equipment allows the Army to develop SSL recommendations from a larger data set. Whereas a single tank company provides 24 months of demand history for each part, 60 tank companies provide 1440 months of demand history for each part. That larger data set leads to the advantages listed across the first row of Table 2.1.

Improve SSL Performance

The Army uses several metrics to evaluate SSL performance:

- *Accommodation rate*: the percent of part requests for which the needed repair part is on the SSL (i.e., has a positive inventory level). The breadth of repair parts stocked on the SSL determines the accommodation rate.
- *Satisfaction rate*: the percent of orders for stocked repair parts that are on hand and available for issue from the shop when needed (i.e., a request is satisfied). The depth of inventory for repair parts stocked on the SSL determines the satisfaction rate.
- *Fill rate*: the percent of part requests that are filled from the SSL. The fill rate is the product of the accommodation and satisfaction rates.

Pooling demands across shops supporting the same equipment to create a larger data set has two primary benefits that allow for higher SSL performance. First, the pooled demand history includes more data from periods in which BCTs were operating at a high tempo; these high-OPTEMPO data are valuable because they are representative of the demand for repair parts in deployed operations. Second, the pooled demand history also has more information about repair parts with low demand rates (i.e., slow-moving parts).

Having additional high-OPTEMPO events in the demand history leads to better estimates of demand variability. Each tank company's two-year history might include only limited periods of high OPTEMPO due to the nature of each BCT's training events and operational assignments.[5] Better estimates of demand variability enable more-informed decisions about the appropriate inventory level needed for each repair part.[6] Appropriate inventory levels are needed for each part stocked on the SSL. As indicated above, determining the appropriate depth of inventory helps to ensure that when a maintainer requests a part, the request can be satisfied.

Having more information about demands for slow-moving parts is beneficial because forecasting the likely demand for these repair parts requires analysis of more data than one shop can provide. Parts with lower demand rates pose a particular problem when executing single shop SSL reviews because of insufficient information to determine typical part demand rates.[7] Pooling demands by shop type results in more data, enabling the identification of a robust mix of slower-moving parts for inclusion on the CSSL. This benefit is reflected in higher CSSL accommodation rates. This is often referred to as *setting the breadth* of the CSSL. Determining the appropriate mix of parts, or CSSL breadth, helps to ensure that, when a maintainer requests a part, the part is stocked on the CSSL.

Ensure CSSL Mobility

CSSL mobility is dependent on the number of different parts and quantity of each part stocked on the CSSL and the storage configuration. When the Army calculated a unique SSL for each shop, the size of the SSL (in terms of the number of different parts and the quantity of each part) and, hence, the storage configuration and mobility varied dramatically across shops of the same type. The CSSLs were developed with specific cube and line constraints.

When all shops of the same type share a CSSL based on their pooled demand history, the Army can define a standardized storage configuration (as was done with CASLs). Using standardized storage configurations across shops of the same type makes it easier to ensure unit mobility across the Army's BCTs.

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[5] For example, depending on timing of the SSL update for a shop in a specific BCT, that BCT might have participated in fewer major training events (e.g., at one of the Army centers capable of hosting brigade-level operations) or rotational deployments.

[6] Inventory levels are set to mitigate the risk of out-of-stock events caused by uncertainties in supply and demand.

[7] Demand rates for each part are derived from several factors: (1) failure rate of the part when the equipment is used (a part can be used on more than one equipment model), (2) quantity of that part in the equipment (e.g., more track pads are used than engines in each tank), (3) usage rate of the equipment (e.g., number of times the equipment is dispatched and mileage per dispatch), and (4) density of the equipment fleet (e.g., there are more high-mobility multipurpose wheeled vehicles (HMMWVs) than specialized construction equipment in a engineering company).

Reduce SSL Churn

When the Army based SSLs on the demand history of single shop, there was the potential for atypical demands for a repair part to have a disproportionate effect on the composition of a unit's SSL. This risk was particularly true for slow-moving repair parts that experienced atypical demands during the review period. By contrast, because the Army bases each CSSL on a pooled demand history, demands that are atypical or localized to one shop or BCT's experience are counterbalanced by the collective demand history of other shops of the same type. As a result, atypical demands are less likely to disproportionately influence the CSSL.

An additional advantage of converting to CSSLs is that the Army has fewer SSLs to update, leaving more time for conducting trade-off analyses to ensure that proposed changes to the CSSL result in meaningful performance improvements. The mathematical optimization formulation—discussed in detail below—makes this trade-off analysis more straightforward.

Shift From the Two-Step Heuristic to Mathematical Optimization

The Army's inventory algorithms have traditionally involved a two-step process. The first step used heuristic business rules to determine which items to stock on the SSL. The second step was to separately calculate how many of each part to stock.

The first step focused on establishing the breadth of the SSL. The Army used heuristic rules to decide which items to add to an SSL, retain on the SSL, and delete from the SSL. These decisions were based on the number of demands for each part during the review period. The *add threshold* specified the number of demands in the review period that were required to add a part not currently stocked to the SSL; the *retain threshold* specified the number of demands in the review period required to retain a part currently stocked on the SSL. If a part on the SSL did not achieve the retain threshold, it would be deleted from the SSL. To reduce the inventory churn, the number of demands required to add a part was set higher than the number required to retain a part. Additional heuristic rules could be used to adjust the add and retain thresholds according to such factors as unit price, unit cube, and whether the item was considered a maintenance-significant part (MSP) or was used primarily on low-density equipment.[8]

The second step focused on establishing the depth of inventory for each part stocked on the SSL. Once the decision was made to stock an item (either add or retain), separate logic was used to calculate the depth. Because the two decisions (breadth and depth) were made independently, there was limited capability to trade off the decision to stock an item against the mobility or cost impact of the depth.[9]

[8] Whether a part is an MSP is determined by how often parts are requested on high-priority work orders Army-wide over the prior three years.

[9] Indexing the depth calculation based on such part characteristics as unit price and unit cube allowed some control of this trade-off, but it was still a rough approximation.

The move to CSSLs afforded the opportunity for the Army to shift from this two-step heuristic approach to a more-flexible and more-effective mathematical optimization approach formulated as an integer program (IP) model and solved using a MIP algorithm.[10] The IP model and MIP algorithm can enforce storage constraints to ensure unit mobility and can use weighting factors to control CSSL churn. Rather than calculate breadth and depth independently, the MIP executes an automated search algorithm that finds the breadth and depth of the highest-performing CSSL that meets the desired constraints. Furthermore, varying the values for the constraints and weighting factors across MIP runs allows analysis of trade-offs in CSSL performance, CSSL cube (which drives unit mobility), and CSSL churn. The advantages of using the MIP algorithm to achieve the goals set by Army leadership for the CSSL—the second row of Table 2.1—are discussed below.

Improve CSSL Performance

A comparison of the CSSLs produced using the two-step heuristic approach and the CSSLs produced by the MIP showed that, for the same level of unit mobility and inventory churn, the MIP-determined CSSLs provided higher performance (i.e., both overall higher MSP fill rate and higher MSP fill rates for critical equipment).[11] The MIP solutions are superior because the trade-offs analyzed by the MIP are more refined and exhaustive versus the two-step approach using add and retain criteria and a separate depth calculation

Another advantage of the MIP is that it can be adjusted to provide higher or lower part support (SSL performance) for different types of equipment in the BCT. When the Army used the two-step heuristic approach, the recommended SSLs provided better parts support to whatever equipment had the highest demands, which is typically the equipment with the highest density in the BCT. For example, the HMMWV, which has the highest equipment density in an infantry battalion,[12] would typically have the most parts that qualified to be stocked on the SSL based on the add and retain criteria. By contrast, using the MIP, weights can be assigned to specific equipment to drive higher or lower parts support by equipment type and focus the CSSL performance on the most mission-critical equipment in the unit.

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[10] A MIP is a generalized problem in which the solution to at least some of the decision variables is limited to integer values. In the case of the determining an CSSL, all the values to be determined are integer.

[11] Given a demand history, the two-step heuristic approach defines a single SSL. One can then set the constraints and churn-weighting functions for the MIP to achieve the same levels for two of the three dimensions of (1) performance, (2) cube (which determines unit mobility), and (3) inventory churn (measured as the value of adds and increases). If cube and churn are held constant in the MIP to that achieved with the two-step heuristic, the resulting CSSL performance over the demand history will be higher for the MIP. One could also configure the MIP to get the same SSL performance and cube at lower SSL churn, or the same SSL performance and churn at reduced cube (e.g., a smaller CSSL).

[12] IBCTs will have an equal mix of HMMWVs and joint light tactical vehicles (JTLV), but most IBCTs currently still have only HMMWVs.

Ensure Unit Mobility

Under the heuristic approach, the recommended SSL would expand or shrink based on the number of demands in the review period. If a unit experienced higher OPTEMPO during the period under review than under the preceding review period, the demand for parts would also typically be higher. This would result in recommendations that would increase the size of the SSL, both in terms of the breadth of parts that were recommended (which would increase the number of storage locations required in the unit) and in the depth or number of each part (which might increase the size of each storage location) and hence reduce unit mobility. The heuristic approach had no mechanism for enforcing unit mobility constraints, other than an after-the-fact manual review. By comparison, the MIP algorithm enforces line and cube constraints (and can even enforce constraints based on the storage configuration available to the unit) and, hence, ensures unit mobility. The MIP algorithm performs an automated search for the SSL with highest performance for the given storage constraints (so only feasible solutions are considered). Also, by making multiple runs of the MIP while varying the storage constraints, it is possible to analyze the trade-off between unit mobility and CSSL performance.

Reduce SSL Churn

By policy SSLs are to be updated annually.[13] Mathematical optimization permits the Army to closely manage inventory churn during the periodic updates of the CSSLs. This is done using churn-weighting factors that, when increased, will reduce the changes from the current CSSL to the recommended CSSL.[14] As the churn-weighting factors are increased, only changes to the CSSL that have the largest benefit in performance are incorporated into the update recommendations. Changes to the CSSL that have little benefit in performance will not be made.[15] Making multiple runs at different churn-weighting factors allows the Army to establish the trade-off between performance and churn during the periodic CSSL update process.

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[13] See AR1710-2.

[14] Two weighting factors are used, one for Army-managed items (AMIs) and one for non-AMIs (NAMIs).

[15] The CSSL for each type of shop involves a subset of fast-moving parts, which must be on the CSSL to achieve high performance, and a choice among a much larger population of slower-moving parts. The increasing the churn-weighting factors limits the amount of change in the latter population while allowing changes that have a more-significant impact on SSL performance. Because the slower-moving parts do not have as large an impact on SSL performance, it might not be worthwhile to substitute large number of slow-moving part for a different group of slow moving parts during a CSSL update if the result is only modest increase in SSL performance. Churn-weighting factors can be adjusted to trade off slightly lower SSL performance to dramatically reduce the need for up-front obligation authority (OA) and workload required at each shop to reconfigure storage, receive and stow new items, and redistribute items no longer on the CSSL. Here slow moving implies parts with a low but nonzero number of demands. Items with no demand will not be retained regardless of the churn factor because they are not passed to the MIP.

Summary

This section described in nontechnical terms the two major changes made to convert to CSSLs: pooling data across shops of the same type and replacing the two-step process with mathematical optimization. These changes helped the Army to achieve the three goals of improving performance, ensuring unit mobility, and reducing inventory churn during the periodic update process. The next chapter provides more detail on the mathematical optimization formulation.

Chapter 3. The Mathematical Optimization Formulation

The prior chapter detailed how pooling demand histories across shops of the same type and shifting from a two-step process to a mathematical optimization formulation addressed the three goals the Army had laid out for the CSSL. This chapter provides a more-technical explanation of the formulation.[16]

Mathematical optimization involves selecting the best solution with respect to some criterion (often referred to as the *objective function*) from some set of available (i.e., feasible with respect to some constraints) alternatives. For the CSSL, the mathematical optimization formulation is based on the parts and the quantity of each part on the SSL. Hence, the decision variable and primary output of the MIP algorithm is the inventory level assigned to each part. In this report, we refer to the inventory level as the safety stock (SS).[17] If the SS is set to zero, that part will not be stored on the SSL. The MIP algorithm uses an automated search algorithm to set the SS for each part to maximize a weighted readiness benefit function subject to storage configuration and value constraints. Hence, the solution is the mix and quantity of parts to be stored on the CSSL, represented by an SS for each part.[18]

This chapter has three subsections:

- The first focuses on the objective function—how the benefit associated with each part is computed and how this benefit can be weighted to increase parts support to more-critical equipment, to emphasize parts that are used more frequently on high-priority maintenance work orders, and to reflect the costs of inventory churn.
- The second subsection focuses on the constraints that determine the set of available solutions. This includes storage configuration constraints to ensure that the CSSL is mobile and constraints on the value of the CSSL.
- The third subsection provides a brief description of the MIP algorithm used to solve the mathematical optimization formulation.

[16] This formulation closely mirrors the one presented in Girardini, 2023.

[17] In GCSS-A, each part on the CSSL is assigned an SS. Shop stock in GCSS-A is ordered with an (s,s-1) policy. This means when any part is issued from on hand stock a replenishment is initiated when material resource planning (MRP) is executed. So, the SS is equal to the requirement objective (RO) and the reorder point (ROP) is equal to the SS-1. For example, if the SS =1 the RO =1 and the ROP =0, implying the system will reorder each time a part is issued when MRP is executed. If the SS =2 then the RO =2 and the ROP =1, and again a replenishment will be initiated each time a part is issued and MRP is executed. If the quantity issued is greater than one or there are multiple issues before MRP is executed the replenishment will be for the total quantity issued.

[18] In this formulation, the SS for each part on the CSSL is referred to as the *decision variable* for the mathematical optimization.

Weighted Readiness Benefit

The Benefit Function

The benefit function for each part is constructed to reflect the number of demands that would be filled as the SS is increased. The benefit function is derived from the pooled demand histories. The demand quantities are summed by unit and time period (e.g., month) for each part. Table 3.1 gives an example of the tank companies monthly demand quantities for an individual part. The tank companies are listed in the first column, and the months are labeled Q1 thru Q24 (where Q is short for quantity) along the first row. The cells of the table provide the demand quantities for each of the 24 months for each of the 11 tank companies.[19] For most tank company-month cell entries, the demand quantity is zero (211 of the 264 cells). The greatest demand quantity for any tank company over the 24 months is 12 (at the intersection of row four, labeled "TC 4," and month 10, labeled "Q10"). The 53 tank company-month combinations with a positive demand quantity are highlighted in green. The last two columns give the summed quantity (Total Q) and the number of months (# Months) with a positive demand quantity for each tank company. These values demonstrate how each tank company might make a different decision on whether to stock this part on their SSL and, if so, how many of this part to stock, if the calculation is based only on demands at each tank company. The final row of Table 3.1 provides a sum of the last two columns, which gives the total quantity demanded by all tank companies during the 24 months (137) and the number tank company-months that had a positive demand value (53).

Figure 3.1 displays the resulting cumulative benefit function for the part demands depicted in Table 3.1. In Figure 3.1, the x-axis indicates the SS for the part, that is, the decision variable in the mathematical optimization (solved for by the MIP algorithm). The y-axis indicates the cumulative benefit. As the SS is increased, the cumulative benefit function has a decreasing slope (i.e., there is progressively less added benefit for each increase in SS). The benefit of increasing the SS by one unit is computed by counting the number of periods the item could have been issued from stock to fill customer demand. Examples are given below:

- Increasing the SS from zero to one would result in 53 issues (one for each of the 53 tank company-month combinations with a positive demand quantity). Hence, the slope of the net benefit function is 53 from 0 to 1. At an SS of one, the cumulative benefit is equal to 53.
- Increasing the SS from one to two would have filled tank company demand in only 31 periods (the number of periods in which the demand was greater than one). The slope from one to two is 53 − 22 = 31. Adding a second part to the SS would not add any

[19] Table 3.1 gives an example of the increased data that comes from pooling demands across units of the same type. At the time of this research there were 60 M1A2 equipped tank companies. Analyzing the data by tank company—running 60 individual SSL reviews—could result in different decisions on whether to stock this part and different decisions on the appropriate inventory level at each tank company.

benefit in the 22 demand periods in which the demand quantity was only one. So, at a, SS of two, the cumulative benefit is equal to 84 = 53 + 31.

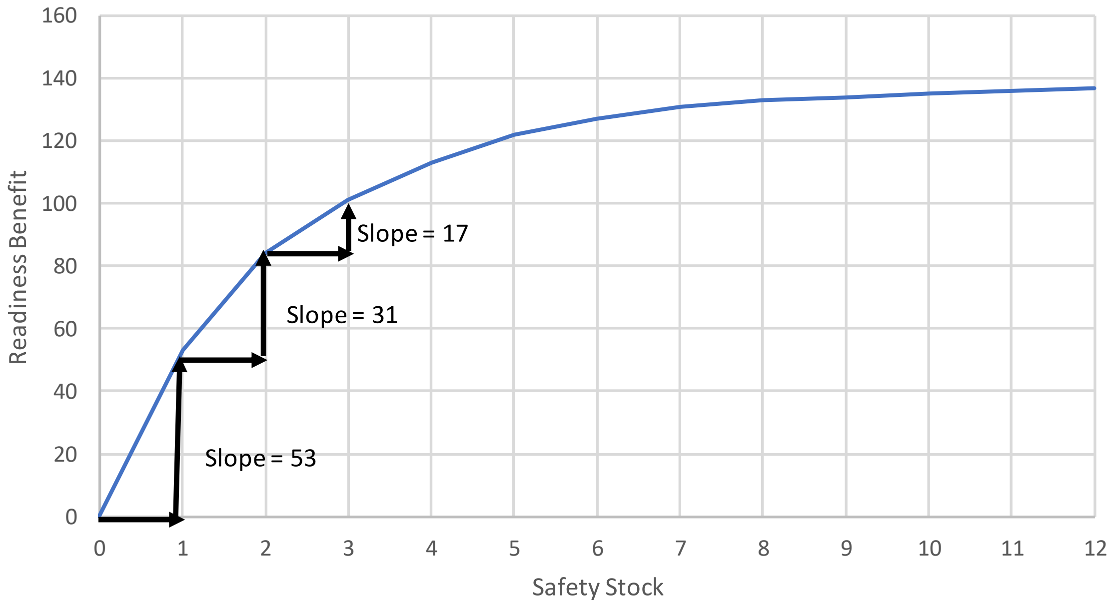
- Increasing the SS from two to three would have filled customer demand in only 17 periods (the number of periods in which the demand was greater than two). The slope from two to three is 53 − 22 − 14 = 17. Adding a third part to the SS would not add any benefit for the 22 demand periods in which the demand quantity was only one or the 14 periods in which the demand was only two. So, at an SS of three, the cumulative benefit is equal to 101 = 53 + 31 + 17.

Table 3.1. Twenty-Four Months of Demand for a Part at 11 Armor (AR) Companies (COs)

ABCT	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20	Q21	Q22	Q23	Q24	Total Q	# Months
AR CO 1	0	6	0	4	0	0	1	0	0	0	1	2	2	0	0	0	0	0	0	0	0	0	0	0	16	6
AR CO 2	1	0	0	2	0	0	0	0	7	1	0	0	1	0	7	0	0	0	1	0	0	5	0	0	25	8
AR CO 3	0	1	0	0	0	8	0	0	0	2	0	2	1	0	3	0	0	0	0	0	0	0	0	0	17	6
AR CO 4	0	0	0	0	0	0	0	0	0	12	0	0	0	0	3	0	0	0	0	0	0	0	0	0	15	2
AR CO 5	0	5	0	0	0	0	0	0	3	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	10	4
AR CO 6	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0	0	0	0	0	4	2
AR CO 7	0	1	0	0	0	0	1	0	1	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0	6	5
AR CO 8	0	0	0	0	0	0	4	1	1	1	0	0	1	5	0	0	0	0	1	0	0	0	0	0	14	7
AR CO 9	0	0	0	0	0	0	0	0	2	2	0	0	0	0	4	0	0	0	2	0	0	0	0	0	10	4
AR CO 10	0	0	0	2	0	0	0	0	0	0	0	0	0	0	3	0	0	0	1	0	1	0	0	0	7	4
AR CO 11	0	2	0	0	0	0	0	0	1	5	0	0	3	0	0	0	0	0	2	0	0	0	0	0	13	5
																									137	53

SOURCE: RAND Arroyo Center analysis of GCSS-A data.
NOTE: Q = quantity.

Figure 3.1. Readiness Benefit Versus Safety Stock for a Part



SOURCE: RAND Arroyo Center analysis of GCSS-A data.

The result of arraying the periods in decreasing quantity and computing the benefit in this way is a piecewise linear function with decreasing slope (defined as a concave function) as the SS increases.[20] A benefit function like that shown in Figure 3.1 is generated from the demand history for each repair part.

Weighting the Benefit Function

The benefit function is weighted by additional factors (besides demand) that either increase or decrease each of the piecewise linear slopes of the benefit function. An increased slope makes the part more desirable for stocking on the CSSL compared with other parts. The weighting factors include the following:

1. The fraction of demands for a part on high-priority work orders that can render the equipment inoperable (referred to as deadlined): The higher this fraction, the more critical it is to stock the part on the CSSL to maintain equipment readiness. A part with a higher fraction of high-priority work orders will get a weight that makes the slope steeper compared with a part with a low fraction of demands on high-priority work orders. The fraction is computed from Army-wide empirical data over the most recent three years.[21]

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[20] A linear function is single constant slope line. A piecewise linear function is a function whose graph is made up of linear (straight-line) segments (see Dantzig, 1963, p. 482).

[21] The fraction must be less than or equal to one and is not allowed to be zero (the minimum value allowed is 0.01).

2. MSPs: A weighting factor to place emphasis on parts that are MSP is chosen by the subject matter expert (SME) executing the run.[22] The SME sets this weight by comparing overall SSL fill rate with the fill rate on the subset of MSP parts to make sure enough emphasis is placed on MSP parts. The SME increases the weight to improve MSP fill rates, but not to the extent that overfill rates fall off the "knee of the curve."
3. Weight on the fraction of units (in this case tank companies) with demand: The fraction of the units that had a demand for the part is computed from the pooled demand history and is the count of rows in Table 3.1 where the entry # Months is greater than zero (e.g., for the part in Table 3.1, this value is equal to 11/11 = 1). This weighting factor is used to place emphasis on parts that get demand across a large proportion of the units versus parts that have many periods of demand in fewer units (the latter are more likely to be atypical demands). The SME sets the weight applied to this fraction.
4. SME-entered equipment weighting factors: A weight can be entered for each type of equipment that the unit supports. If no value is entered for a type of equipment, the default is one. A weight greater than one is used to increase parts support for mission-critical equipment (e.g., M1A2 in a tank company). A value less than one could be used to reduce the parts support for equipment that is not as mission critical (e.g., the HMMWV or joint light tactical vehicle [JLTV] in a tank company). The equipment weights are used to compute an equipment importance weight for each part.[23] The output includes work order fill rates by equipment type so the SME can use the output to quickly determine if parts support by equipment type requires adjusting the weighting factors.
5. SME-entered churn factors: There is a separate weighting factor for AMIs and for NAMIs. These factors are described in more detail below. The SME will typically make multiple runs at different levels of churn-weighting factors to establish the trade-off between CSSL performance and the transition costs to execute the CSSL update. The final decision on the trade-off is typically determined with guidance from higher-level headquarters.

Weighting factors 1 through 4 above are multiplied to obtain a single weight for each part, which is applied to the benefit function for that part. So, each slope of the piecewise linear function is multiplied by the same scalar value. Because the weights vary by part, this changes the trade-offs across parts by affecting their relative slopes. Consider a part 1 and a part 2 that both have the same demands as in Tables 3.1. Table 3.2 gives the weighting factors for part 1 and part 2: The weighting factors for part 1 multiplied together give the combined weight of 1.5, and the weighting factors for part 2 multiplied together give the combined weight of 0.4.

[22] MSPs are determined using the same empirical data used to compute the fraction deadlining (Army-wide data over three years). The designation of MSP is based on thresholds on the number or percentage of deadlining demands applied by equipment model. If a part exceeds the thresholds for any model, it is designated as an MSP.

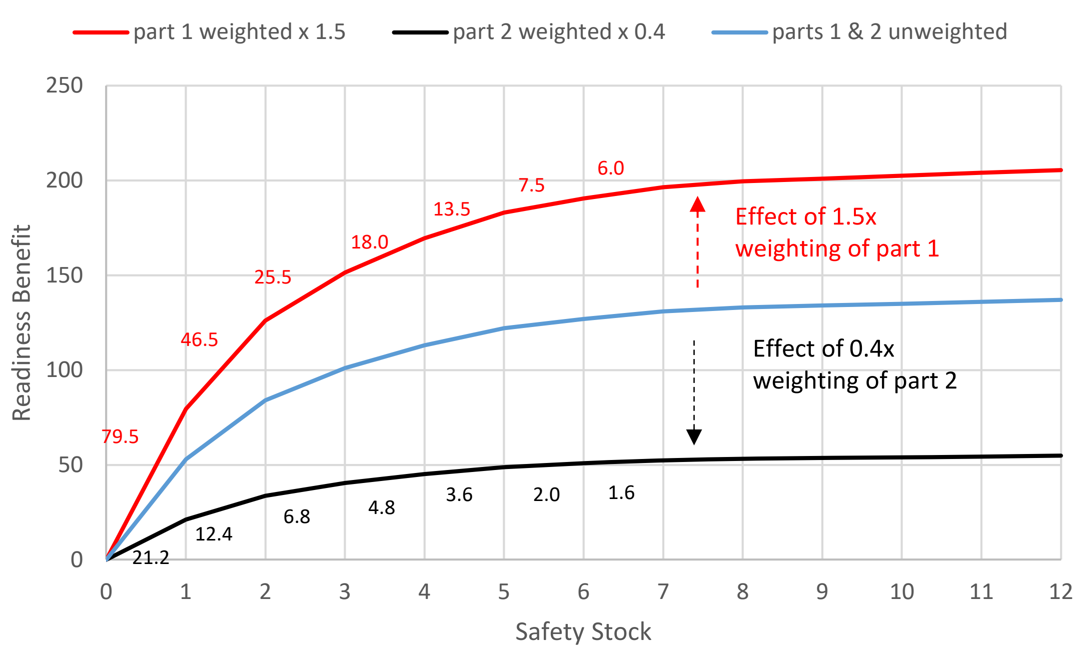
[23] In GCSS-A tables, parts are linked to work orders, and work orders are linked to the equipment type being worked on. These links are used to sum across all work orders and part orders to translate the equipment weights to part weights. Some parts are used on more than one type of equipment.

Table 3.2. Example Weighting Factors

	Part 1	Part 2
Fraction of deadlined demands	0.75	0.2
MSP weight	1	1
Fraction of shops with demand	1	1
Equipment weight	2	2
Combined weight	**1.5**	**0.4**

Figure 3.2 shows the resulting cumulative weighted readiness benefit function for each part and the slopes of the piecewise linear segments. In this case, after the weighting factors are applied, part 1 looks more attractive than part 2. Comparing the slopes of the cumulative benefit functions, one would raise the SS for part 1 from zero to three before raising the SS of part 2 from zero to one. That is, the slope for increasing the SS of part 1 from two to three is 25.5, which is greater than the slope of 21.2 associated with increasing the SS for part 2 from zero to one.

Figure 3.2. Effect of Weighting on Readiness Benefit of Two Parts with Same Demands



SOURCE: RAND Arroyo Center analysis of GCSS-A data.

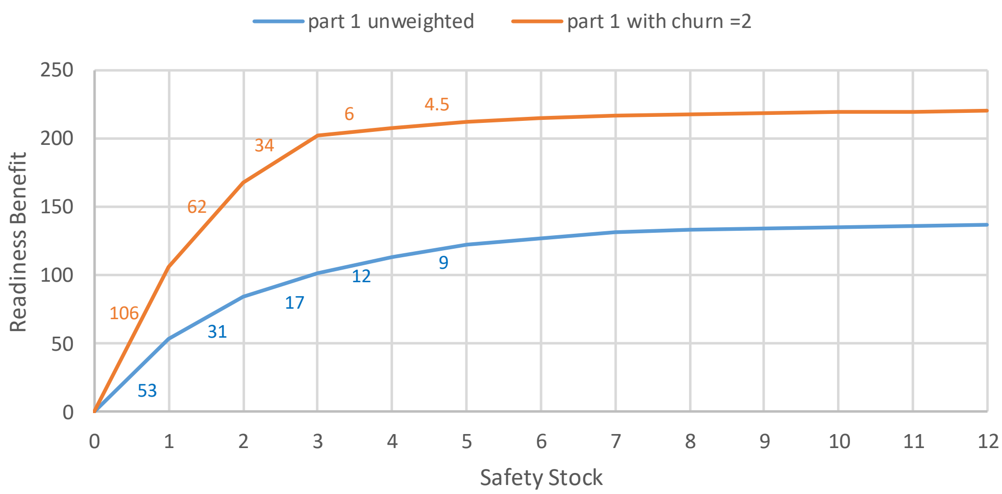
The churn factors are applied differently from the other weighting factors.[24] As described in the previous section, the intent of the churn weighting factor is to limit change on the SSL unless the change results in enough performance improvement to justify the associated cost and workload. To discourage change that does not meaningfully improve performance, the churn weighting factors are used, changing the slope of the benefit function above and below the current SS for a part so that (1) the benefit of increasing the SS (or adding the part to the SSL if it is not currently stocked) is reduced and (2) the reduction in benefit of decreasing the current SS is larger. Hence, it becomes more desirable in terms of the net weighted benefit function to keep the SS at the current level unless the change in the net benefit function is more substantial.

Assume the part with demands shown in Tables 3.1 has an SS of three. Applying a churn factor of two would multiply the slopes from zero to three by two and divide the slopes from three to 12 by two. Figure 3.3 shows how the original benefit function given in Figure 3.1 is translated by the churn factor of two. The effect of the churn factor of two is to make the SS value of three the "knee of the curve." That is, the curve will rise very sharply from zero to three and then flatten out beyond three as the churn factor is increased. The purpose of the churn factors is to avoid a lot of actions that increase/decrease/add/delete the SSs that do not meaningfully change the performance of the CASL.[25]

[24] The MIP was formulated with separate AMI and NAMI churn factors. This was developed to offer better control when updating CASLs, where increases and adds for NAMI items are typically an immediate cost to the AWCF. By comparison increases or adds for AMI may only involve reallocating existing AWCF inventory.

[25] The current SS for all parts on the SSL is referred to as the *set point*. Increasing the churn weights controls how much the recommendations will change from the set point. Parts on the set point that have no demands are not passed to the MIP so they will always be deleted from the CSSL.

Figure 3.3. Effect of Churn Factor of Two on the Readiness Benefit



SOURCE: RAND Arroyo Center analysis of GCSS-A data.

Constraints

When searching for the SS levels that produce the highest-performing SSL, the mathematical optimization must stay within the available set of solutions. The available set of solutions is defined by linear constraints on storage configuration and capacity and value.

Storage Configuration and Capacity

The SSs that are searched to maximize the weighted readiness benefit function must adhere to the unit's storage configuration. The storage configuration is defined by the number of storage locations (the number of parts with an SS over zero) and the extended cubic feet. The extended cubic feet constraint is based on the maximum number of parts expected to be in storage times the unit cube summed over all parts. The MIP solver assigns the SS for each part (the decision variable), which is equal to the requirement objective (RO) for shop stocks in G-Army (which are replenished each time a part is issued). Both constraints can also be enforced by storage categories. The CSSL formulation currently uses three storage categories, bin, shelf, and bulk, that reflect the common types of storage capabilities in units. Parts are assigned a storage category based on part characteristics (e.g., unit cube) and an estimate of the extended cube (quantity times unit cube) that is expected to be in the storage location. The SME can set the number of locations and the extended cube constraint values for the overall SSL and for each storage category. However, once the CSSL is set, unless there is guidance to either expand or reduce unit storage, the constraint values are typically computed from the existing CSSL to avoid having to reconfigure the unit storage locations.

If the Army can develop standardized storage configurations for shops (like what was done for CASLs), the bin and shelf storage categories can include information on the maximum quantity that can fit in the existing storage location, referred to as the opening capacity. So, for parts stored in bin and shelf locations, we can also define an upper bound for the SS for each part. Analysis can then be done with these constraints active and inactive to evaluate if some parts should be assigned a different storage location to allow for a larger quantity to be stored. If the increase in performance is significant when the constraints are inactive then it would be worthwhile to adjust the existing storage configuration (referred to as a planograph). If the performance increase is not significant when the constraints are inactive, it is not worthwhile to adjust the existing storage configuration.

Value Constraints

There are two ways to address constraints on the value of the inventory. The first is constraining the total value of all the parts on the CSSL. This is simply the sum of the SS times the unit price, which is a single linear constraint involving the SS levels (the decision variables).[26] One can then execute the MIP at different levels of inventory value to generate different CSSLs and compare the performance. Because an CSSL is stored at multiple shops, it is important to multiply the cost across all the units that use that CSSL.

A second approach applies if the value of the current inventory is considered a sunk investment. Then, the problem is one of marginal (or transition) cost of updating the CSSL versus improving CSSL performance (i.e., this approach focuses on the problem of how best to get from the current inventory to an improved inventory). All that matters from a cost constraint perspective is the cost to update to the new recommended SSs from the current SSs. The churn-weighting factors are integrated into the weighted benefit function and used to control the transition costs. The transition costs can be monetary (e.g., the costs required to add new parts or increase the SS of parts already on the CSSL) or related to workload (e.g., reconfiguring storage in the unit). If the constraint on CSSL extended value remains constant, the value of SS additions and increases will be offset by deletions and decreases. The transition cost for the upgrade can be computed from the current inventory, represented by the parts on the current CSSL and the associated SSs (referred to as the set point), to the new parts and associated SSs (recommendation) output from the MIP. As shown in Figure 3.3, increasing the churn-weighting factors makes the current set point look more favorable, and the resulting optimal solution will have lower transition costs. Varying the churn-weighting factors allows the SME to analyze the trade-off of CSSL performance and the transition costs when executing a CSSL update.

[26] One could also use the unit price minus the unserviceable credit in place of the unit price.

Execution of the MIP Algorithm

Numerous commercial-off-the-shelf MIP algorithms exist.[27] We used the MIP algorithm that is part of the SAS/OR statistical package. This is the same algorithm used to compute CASLs for Army BCTs. We also use SAS to process the data, compute the weighted benefit function and constraints, and put the data in the format required by the MIP solver. The data processing includes cleansing to detect and trim outlier values (e.g., outliers on demand quantity) and correct other data quality problems.

The MIP algorithm uses an automated search procedure (branch and bound) and solves multiple noninteger (i.e., where the SS can be fractional) piecewise linear optimizations to determine the integer SS values that maximize the readiness benefit function while satisfying the constraints.

The output of the MIP algorithm is a list of parts and their associated SS values. Extensive postprocessing and simulation are then executed in SAS to compare the MIP output to the set point, or the current SSL, in terms of the multiple dimensions of performance, storage, and value and to compute transition costs.

[27] Because all the SSs must be integers (cannot be a fraction of a part), this is formally an integer programming problem. However, MIP solvers are generalized code that can handle problems with all integer decision variables or a mix of integer and continuous decision variables.

Chapter 4. Conversion of the Army's Armor, Infantry, and Stryker SSLs to CSSLs

Because of the significant variation across SSLs in the Army ground BCTs of the same type (in terms of which parts were on the SSLs and the depth of each part), the Army recognized that conversion to a CSSL would require significant changes to SSLs across the ground BCT shops. This section provides a brief description of how the mathematical optimization was formulated for the initial conversion, the forecast of the benefits of converting to the CSSLs, tracking of progress in implementing the CSSLs, and the tracking of CSSL performance metrics after implementation.

Formulation for the Conversion Runs and Forecast Benefits

Analysis of the current SSLs across each of the BCT types revealed that there was very high variability in the SSLs across units supporting the same equipment, both in terms of breadth and depth. Figure 4.1 shows three specific unit types in the ABCT, the armor companies, mechanized infantry companies, and artillery batteries. Around forty percent of each of these unit types had no shop stock or bench stock to speak of (i.e., ten or less parts with inventory levels on shop or bench stock). We simulated the performance of inventory levels at the units that had levels against the most recent 24 months of part reservations linked to workorders. For performance we focused on high priority work order fill rate (Hi Pri job fill rate [FR]) and high priority work order fill rate for the critical weapon system (Hi Pri Job FR Key WS) in each unit type. To count as a fill all the parts on the high priority work orders had to be filled. The 40 percent of units with ten or less lines of bench or shop stock were not included so as not to bias the simulation results. The remaining units averaged 125 to175 lines with inventory levels depending on unit type. The simulation results showed the expected fill rate from shop and bench stocks in the remaining units was less than 10 percent. The fill rate remained less than 10 percent when measured on the subset of workorders associated with the key weapon system for each unit type.[28]

Across all the units, even those with ten or less lines of shop or bench stock, there was considerably more inventory showing in the system as on hand (OH). The average was from 330 to over 400 different parts on OH depending on unit type (or about 8 times as many unique parts OH than with inventory levels worth about 4 to 5 times the value). Across units supporting the same equipment there was a lot of variability as to what parts were OH. It is less clear why there

[28] When simulating we tracked several performance metrics including overall class IX (repair part) fill rates, maintenance significant part (MSP) fill rates, and overall work order fill rates. Performance across all these metrics was similar (i.e., less than 10 percent). We report high priority work order fill rate as that is expected to be the metric most closely aligned with equipment readiness.

would be so much inventory OH if there was not an inventory level. One theory is that the OH was a result of parts ordered for work orders that was provided to maintainers to complete jobs but not issued to the job. Hence, these parts appear to be OH, but are not really OH. Another possibility is that parts were ordered for work orders, but then obtained through some other mechanism (i.e., obtained from a sister unit that already had the part OH or from vendor replenished bins maintained in the motor pool). Hence, when the ordered parts arrived, they remained OH. We simulated the performance of the OH as well. The performance of the OH was considerably higher than the performance of the parts with inventory levels. Because we simulated against historical work orders, this was to be expected if the OH was generated from ordering for past workorders.

Figure 4.1. Performance of Current Inventory Levels and On-Hand Inventory

	ABCT Armor Companies						
	# of Shop Stocks	**# Lines**	**Cube**	**Value**	**Hi Pri job FR**	**Key WS**	**Hi Pri Job FR Key WS**
Current	34*	6,012	12,923	$ 48,840,000	7%	M1A2	10%
OH	60	25,168	92,082	$ 170,829,000	24%	M1A2	28%
* 26 of 60 Armor COs currently have < 10 lines of shop and bench stock (6 have no lines)							
	ABCT mechanized infantry companies						
	# of Shop Stocks	**# Lines**	**Cube**	**Value**	**Hi Pri job FR**	**Key WS**	**Hi Pri Job FR Key WS**
Current	36*	4,457	8,036	$ 37,107,000	5%	M2A3	9%
OH	65	21,519	63,900	$ 112,472,000	19%	M2A3	25%
* 29 of 65 MECH INF COs currently have < 10 lines of shop and bench stock (19 have no lines)							
	ABCT Artillery batteries						
	# of Shop Stocks	**# Lines**	**Cube**	**Value**	**Hi Pri job FR**	**Key WS**	**Hi Pri Job FR Key WS**
Current	17*	2,610	2,733	$ 6,636,000	4%	M109A6	6%
OH	30	12,660	30,732	$ 33,310,000	21%	M109A6	29%
* 13 of 30 artillery BTRYs currently have < 10 lines of shop and bench stock (3 have no lines)							

SOURCE: RAND Arroyo Center analysis of GCSS-A data.
NOTES: OH = on hand; Hi Pri job FR = high priority work order fill rate; Hi Pri Job FR Key WS = high priority work order fill rate for the critical weapon system.

To limit the upfront inventory investment and workload required at conversion, it was desirable to favor parts that were or appeared to be OH in each of the unit types. Hence for each unit type we established a set point by selecting parts that were the most common by unit type. There was not a lot of commonalities, so thresholds were established by looking across units with the same equipment. For example, the OH at each armor company was analyzed with thresholds on the number of armor companies that had a specific part OH. If the number was greater or equal to the threshold then that part was added to the set point. If not, the part was not part of the set point. For parts added to the set point, the depth for the part was set as the average of the OH for armor companies where the OH > 0. The set point and churn-weighting factors described in the mathematical optimization formulation were then used when executing the MIP algorithm to arrive at an CSSL with reduced conversion costs.[29] This process was repeated for each unit type with an CSSL.

Due to the lack of commonality in the OH across the different units of the same type, the set points tended to have less breadth than needed. SMEs were consulted to determine which unit types should have an CSSL and to set storage and value constraints for the MIP run for each unit type. Figure 4.2 summarizes the results for each unit type with an CSSL.

It was determined that in the ABCT most companies (e.g., an armor company) should be able to operate independently (e.g., as or part of a task force) with an element of the forward support company (FSC) in support. Hence, in the ABCT ten different types of companies were provided a CSSL. These ten different CSSL types were arrived at by analyzing the property book to determine equipment differences across unit types and discussion with SMEs. Some are straight forward. For example, the armor company primarily supports the 14 M1 tanks and there are six armor companies per ABCT. At the time there were ten ABCTs so the CSSL run used demand history from 60 armor companies along with the set point discussed above and the constraints from Figure 4.2 to compute the CSSL to be used at all 60 armor companies.[30] By comparison of the five FSCs in the ABCT, four have similar equipment, but the Fire Support Company (F FSC) supporting the field artillery battalion (BN) has palletized loading system (PLS) truck and trailers which have the capacity needed to resupply artillery ammunition to the self-propelled artillery batteries. Hence the F FSC received a different CSSL than the other FSCs that do not support PLS. For the ABCT, the CSSLs for the FSCs are to support the organic equipment used by the FSC. Because the CSSLs in the ABCT are essentially held at CO level, there are 29 CSSLs per ABCT.

For the IBCTs and SBCTs, the SMEs felt that the BN was a more natural level of organization for the CSSLs. Hence, the SMEs recommended that the CSSLs for the FSCs support not only the equipment in that FSC but also the equipment of the supported BN. The field maintenance CO (always designated the "B" or "Bravo" CO) would support the other

[29] Conversion costs were computed by comparing the OH for each National Item Identification Number (NIIN) to the CSSL recommended inventory level for that NIIN.

[30] If some AR COs are equipped with different models of the M1 tank, then an empirically derived bill of materiel (BOM) was used to filter the CSSL. Each such filtered CSSL was referred to as a variant of the CSSL for the AR CO.

companies of the brigade support battalion (BSB). The result was five different unit types assigned CSSLs in the IBCT and the SBCT. For the SBCT separate runs were made for SBCT equipped with flat bottom (FB) Stryker and those with the double V hull (VV) Stryker, so there were ten different types of CSSLs for the SBCTs.

Figure 4.2. Summary of the CSSLs

ABCT	# of Shop Stocks per BCT	# Lines per Shop Stock	# FPU/TEU per Shop Stock	$(K) Value per Shop Stock	$(K) Shop Stock per BCT
Armor	6	175 (350 bench)	1 (263 cu ft)	$ 660	$ 3,960
Rifle/Mech	7	200 (325 bench)	1 (263 cu ft)	$ 660	$ 4,620
Battery	3	250 (275 bench)	1 (265 cu ft)	$ 660	$ 1,980
F FSC	1	250 (275 bench)	1 (263 cu ft)	$ 330	$ 330
D, G, H, J FSC	4	215 (310 bench)	1 (263 cu ft)	$ 265	$ 1,060
BSB Bravo CO	1	260 (265 bench)	1 (263 cu ft)	$ 660	$ 660
combat eng A CO	1	250(275 bench)	1 (263 cu ft)	$ 660	$ 660
combat eng B CO	1	365 (160 bench)	1 (263 cu ft)	$ 660	$ 660
BEB/ E FSC	1	250 (275 bench)	1 (263 cu ft)	$ 414	$ 414
T CO (BN HHC)	4	245 (280 bench)	1 (263 cu ft)	$ 660	$ 2,640
	29				$ 16,984

IBCT	# of Shop Stocks per BCT	# Lines per Shop Stock	# FPU/TEU per Shop Stock	$(K) Value per Shop Stock	$(K) Shop Stock per BCT
Inf BN + G,H, or J FSC	3	314 (361 bench)	1 (170 cu ft)	$ 150	$ 450
CAV SQN + D FSC	1	305 (370 bench)	1 (250 cu ft)	$ 150	$ 150
Fires BN + F FSC	1	318 (367 bench)	1 (275 cu ft)	$ 250	$ 250
BSB Bravo CO	1	347 (403 bench)	2 (350 cu ft)	$ 250	$ 250
BEB + E FSC	1	314 (361 bench)	1 (250 cu ft)	$ 150	$ 150
	7				$ 1,250

SBCT	# of Shop Stocks per BCT	# Lines per Shop Stock	# FPU/TEU per Shop Stock	$(K) Value per Shop Stock	$(K) Shop Stock per BCT
Inf BN + G,H, or J FSC	3	345(255 bench)	1 FPU + 1 FR (bulk)	$ 1,500	$ 4,500
CAV SQN + D FSC	1	350 (250 bench)	1 FPU + 1 FR (bulk)	$ 1,400	$ 1,400
Fires BN + F FSC	1	350 (250 bench)	1 FPU + 1 FR (bulk)	$ 1,250	$ 1,250
BSB Bravo CO	1	300 (300 bench)	1 FPU + 1 FR (bulk)	$ 750	$ 750
BEB + E FSC	1	345(255 bench)	1 FPU + 1 FR (bulk)	$ 1,200	$ 1,200
	7				$ 9,100

SOURCE: RAND Arroyo Center analysis of GCSS-A data.
NOTES: FSC = forward support company; eng = engineer, CO = company; CAV SQN = cavalry squadron; BEB = brigade engineering battalion; BN = battalion; HHC = headquarters company; BSB = brigade support battalion; FPU = field pack-up unit; TEU = twenty-foot equivalent unit; BCT = brigade combat team.

Each of the CO level CSSLs in the ABCT was assigned a constraint on the extended cube of the CSSL parts (safety stock level times the unit cube summed over all parts on the CSSL) that could be stored in with a single field pack-up unit (FPU) or twenty-foot equivalent unit (TEU). Similarly for the BN-level IBCT CSSLs, except the field maintenance (bravo) company of the BSB which was allotted higher cube constraint. It was determined by SMEs that the SBCT CSSLs would require wheel assemblies, a few larger assemblies, and line replaceable units (LRUs) to support equipment readiness for the Stryker vehicles. Hence, the SBCT CSSLs were allowed a flat rack for CSSL storage which was reflected in a higher cube constraint for bulk storage.[31]

All the runs were restricted to 500 unique lines based on input from SMEs. The 500-line limit included both shop stock and bench stock (see Appendix A for the definition of bench stock). However, the CSSLs included only the items that were for shop stock (did not qualify as bench stock). Only the CSSL recommendations were implemented.[32]

Example Tradeoff Analysis

Once the constraints and set point were set the primary tradeoff analyzed when developing the CSSLs was associated with the equipment weighting factors. First recommendations were computed with all the equipment for each CSSL type having a weight of one. SMEs reviewed the results (e.g., number of parts and dollar value by equipment type and simulation results that show NMC work order fill rate by equipment type) focusing on how the CSSL supported the different equipment in the unit type and suggested changes to increase support for more critical equipment (e.g., equipment with an equipment readiness code [ERC] = "P" for the unit type). Figure 4.3 gives an example of how the equipment weighting factors were used to analyze part support across the different types of equipment supported. For this unit type, the dominant equipment in terms of workorders opened and parts ordered was the HMMWV. Hence, with the default equipment weight of one for all equipment (see "no wgt" on the X-axis) the initial recommendations result in a deadline job fill rate for HMMWVs of almost 60 percent (yellow line and markers) which is much higher than the overall unit fill rate which is 40 percent (blue line and markers). The SMEs established a preference for other equipment (e.g., crew served weapons which were deemed more important to unit combat effectiveness). However, in the run with no weights the equipment deemed most critical by the SMEs (orange line and markers) had a fill rate of less than 10 percent. Furthermore, for all the equipment the SMEs felt was more

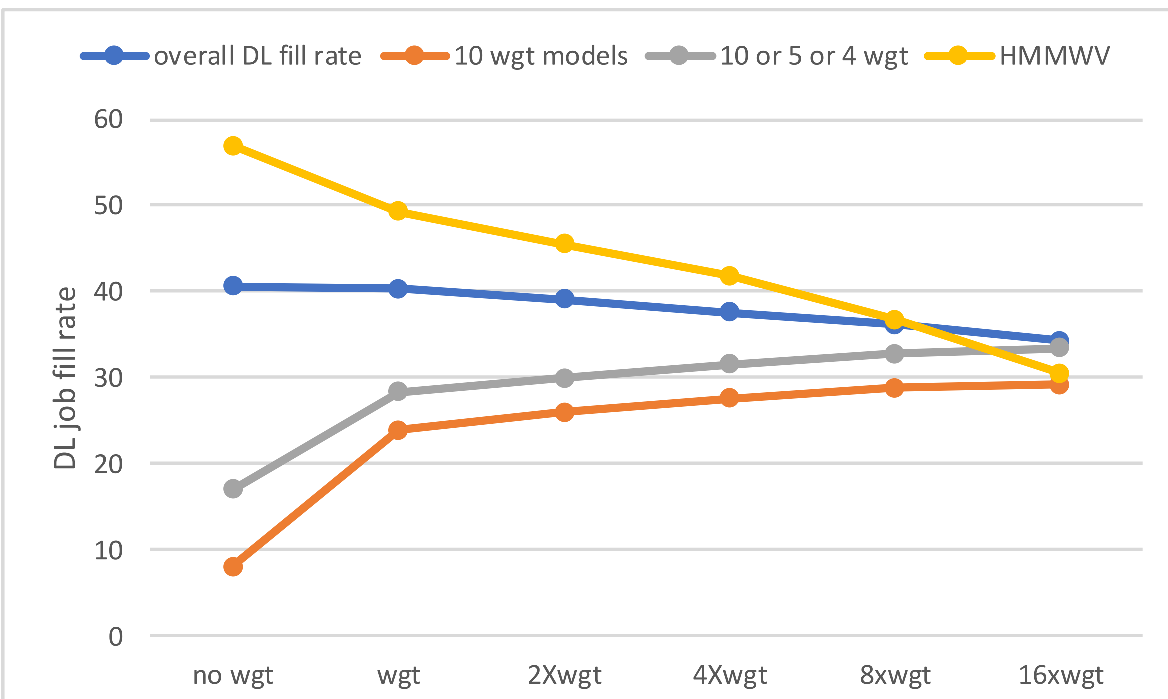
[31] By increasing the total cube constraint and the bulk cube constraint, while keeping the bin and shelf constraints constant additional storage is limited to items appropriate for storage on a flat rack (based on unit cube times a RO expected to get an 85 percent fill rate). Similarly, bin and/or shelf storage along with total capacity could be increased and bulk storage held constant if more bin and shelf storage were made available.

[32] At the time some of the units had bench stocks in the motor pools that were periodically replenished by vendors.

critical, the fill rate was ~17 percent (grey line and markers), well below the fill rate across all equipment of 40 percent

Based on input from the SMEs in the next run the most critical equipment was assigned an equipment weight of 10 and other critical equipment was assigned weights of 5 or 4 (see "wgt" on the X-axis for the results of this run). This dropped the HMMWV fill rate to just under 50 percent and the critical equipment had fill rates between 25 (for the most critical equipment) and 30 percent. The research team then ran a series of parametric runs increasing the equipment weights by an increasing factor (2 times, 4X, 8X and 16X). Increasing the weights continued to improve the fill rates of the more critical equipment and reduced fill rate of the other equipment in the unit, most specifically the HMMWV fill rate. Note also that the overall unit fill rate went down as well. In general, as the weights increased on the critical equipment faster moving parts used to repair the HMWWV were displaced off the CSSL by slowing moving parts used to repair the SME-judged more critical equipment.

Figure 4.3. Effect of Equipment Weights on Unit Fill Rates



SOURCE: RAND Arroyo Center analysis of GCSS-A data.
NOTES: DL = deadline; wgt = weight; HMMWV = high mobility multipurpose wheeled vehicle.

After the tradeoffs were established, the CSSLs in table 4.2 were computed. Simulation results for overall high priority work order fill rate and high priority workorder fill rate for critical weapon systems (e.g., ERC = P) increased from the 6 percent to 10 percent shown in Table 4.1 to 30-35 percent. The highest performance was achieved for units where the ERC = P weapon systems accounted for most of the unit's work orders (e.g., the Abrams tank in the armor company).

Implementation of the CSSLs

The CSSL recommendations were reviewed by SMEs resulting a small number of changes at the part level.[33] Where new materiel fielding had or was scheduled to occur the decision was made to simply take out parts that were unique to the equipment being replaced. For example, any parts unique to the M1A2SEPv2 were removed if armor CO had already been or was scheduled to be fielded with the M1A2SEPv3.[34,35]

Then the challenge was how to post the large number of CSSL recommendations represented by Figure 4.2 across all the correct plant 2000 storage locations (SLOCs) in the ground BCTs. To expediate the process Army Shared Services Command (ASSC) developed a staging table that could be used to post all the different types of CSSLs. ASSC also developed a transaction code (T-code) that the units could use to copy the correct CSSL to the unit SLOC. The research team worked with ASSC to standardize the CSSL naming convention and provided a master mapping to make sure the correct CSSL was copied to the correct SLOC. The T-code established the CSSL levels as materiel requirement planning (MRP) type "ZV" with an ROP with forecast and replenishment turned off. This allowed units to turn replenishment on when they were ready to fund, receipt, and store the parts on the CSSL.

Units were encouraged to post the CSSL to their SLOCs even if they could not currently fund, receipt and store the parts. The research team established metrics in Vantage that tracked and compared the inventory levels at each SLOC and compared it to the recommended CSSL. These comparison metrics were then rolled up to various management levels (e.g., brigade, division, Corps, Major Command, and overall). Figure 4.4 tracks the extent to which the inventory levels at the ground BCTs match the CSSL recommendations posted to the staging table. The blue line tracks the percent of CSSL value that is posted to the unit SLOCs. The orange line shows the percent of lines (e.g., unique SLOC part combinations) that match the CSSLs and are posted to the unit SLOCs.[36] The dashed blue line tracks the value of unit inventory levels that matched the CSSL and had replenishment turned on (all other inventory

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[33] While some SMEs provided a part level review of the CSSL recommendations, it was more productive to get SME input during the tradeoff analysis as the constraints and weighting factors are set. Having the SMEs engaged earlier in the analysis results in fewer part level changes, which tend to be more tedious.

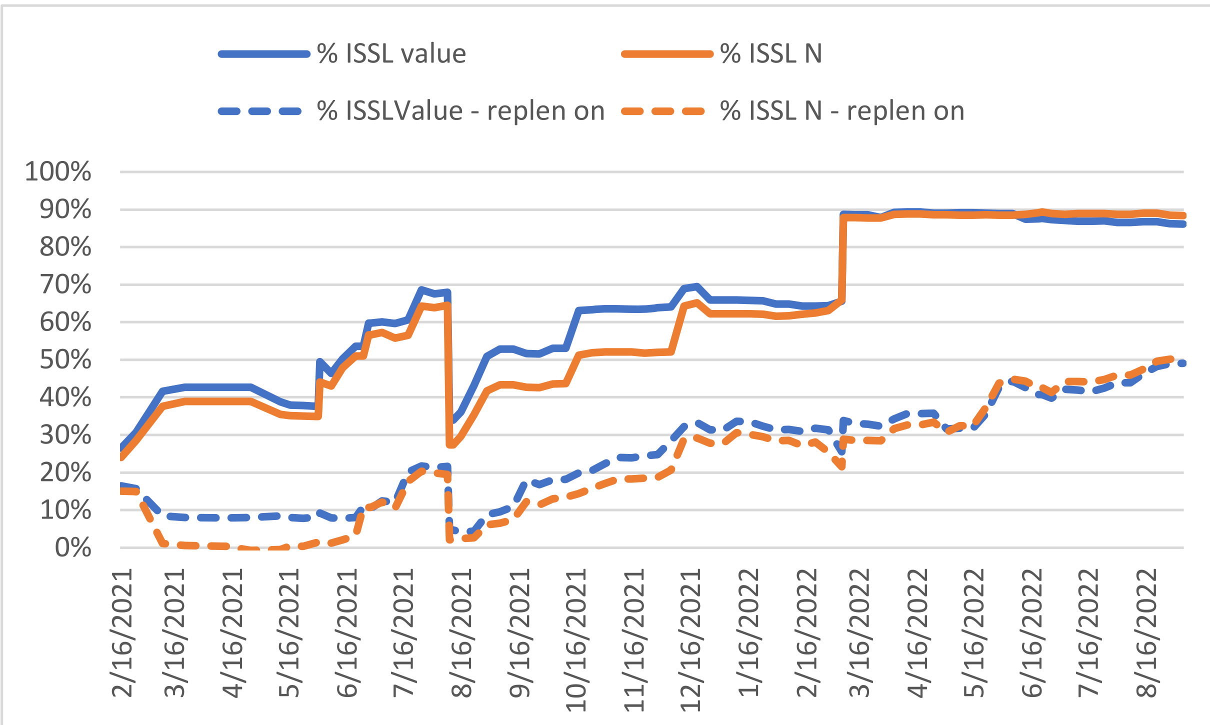
[34] The bill of materiel (BOM) for the M1A2SEPv3 was used to identify parts recommended based on the M1A2SEPv2 demand history that no longer applied.

[35] The decision was made to lave holes in the CSSL due to lack of demand data on the new systems and uncertainty on how parts for the newly fielded systems would be funded.

[36] To make the metrics more accessible to unit personnel (not all of whom were regular users of Vantage), the metrics were also implemented in the Commander's Actionable Readiness Dashboard (C@RD, pronounced "card") which is accessible through the G-Army portal.

levels that matched the CSSLs up to the solid line were posted but had replenishment turned off). Likewise, the dashed orange line tracks the percentage of lines (e.g., unique SLOC part combinations) that matched the CSSL and had replenishment turned on. Figure 4.4 shows that while 90 percent of units copied their CSSL levels from the staging table by March of 2022, only about 33 percent had activated the levels by turning replenishment on (by unchecking replenishment off indicator). That had increased to about 50 percent 6 months later.

Figure 4.4. Tracking the Posting of the CSSLs to Unit SLOCs



SOURCE: RAND Arroyo Center analysis of GCSS-A data in Vantage.
NOTES: CSSL value = extended value of CSSL; CSSL N = number of unique parts on the CSSL; replen on = replenishment on.

Unlike in the case of the CASLs, there was no standard storage configuration developed for the CSSLs. When replenishment was turned on, units used whatever containers and storage aids they had on hand to store the CSSL. Hence there was no standard planograph (e.g., each armor CO would likely store the same CSSL differently).[37]

[37] For the CASLs, each BCT of the same type was provided with the same containers and storage aids in the containers. Hence, Army Sustainment Command (ASC) packaging and preservation used software to develop a standardized storage plan, referred to as a planograph, for the CASL inventory recommendations. As a result, each ABCT had the same storage plan (i.e., part A was in the same container and storage location within that container in every ABCT).

Tracking CSSL Performance

There were not transactional metrics established for tracking shop stock performance in GCSS-A. To calculate CSSL performance one would need to know what inventory levels were posted at the time MRP was executed. Lacking this data the research team used monthly data extracts from GCSS-A to track CSSL performance. The monthly "snapshots" of the inventory levels were used to compute accommodation rates for the transactions occurring in the prior month. How well this reflected actual accommodation rates depended on the how much change there was to the inventory levels during the month.[38] A reservation is considered accommodated if there is a nonzero safety stock or reorder point at the SLOC. There was no check made to see if replenishment is on or off in the monthly snapshot (this can be updated based on funding levels and was considered to dynamic to include in the metric). Satisfaction rates were computed based on whether a part reservation resulted in a purchase request (PR) being generated during MRP. The fill rate is the accommodation rate times the satisfaction rate (so to be filled a part reservation must be accommodated). If part is accommodated but a PR is generated it implies the current inventory position is insufficient to fill the reservation quantity. If no PR is generated, then the reservation quantity is either on hand or already due in, so this counts as a fill.[39] Figure 4.5 gives the accommodation and fill rates aggregated across the ground BCTs for all Class IX.

Figure 4.6 gives the accommodation and fill rates aggregated across the ground BCTs limited to the subset of maintenance significant parts (MSP). The accommodation rates trended upward as units posted their CSSLs from the staging table. However, satisfaction and, hence, fill rates remained lower than anticipated (based on simulations of the CSSL levels against demand history). This is due to many units posting the CSSL levels but not turning replenishment on (by unchecking replenishment off, see dashed lines in Figure 4.4). Some of the reasons given for units posting levels but not turn replenishment on were (1) lack of funds, (2) lack of time to process workload (e.g., engaged in rotational deployment or key field training exercise), (3) need to improve inventory accuracy in plant 2000 before bringing in more stock, and (4) need to organize or procure storage containers or storage aids. In some cases, replenishment was alternated between on and off based on the status of funds.

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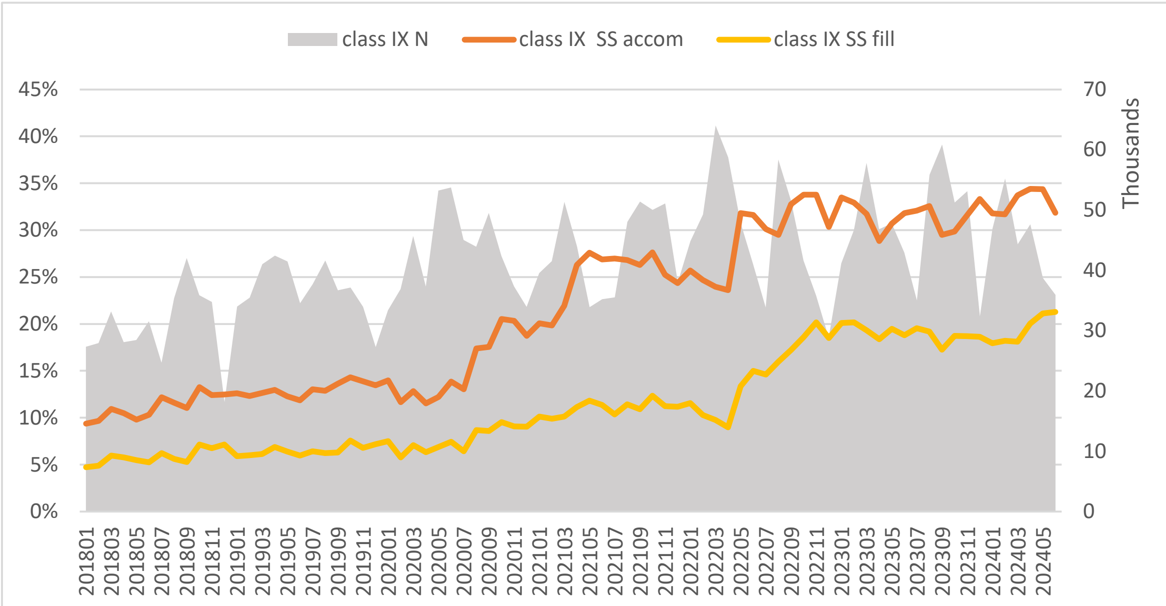
[38] If there was a lot of change to the inventory levels during a month the accommodation rate would be less accurate. There were also a couple months after the staging table was established where the monthly snapshot file was corrupted, so the prior month data and to be reused. Hence, the trend in accommodation rate is more important than the exact month when rates increased.

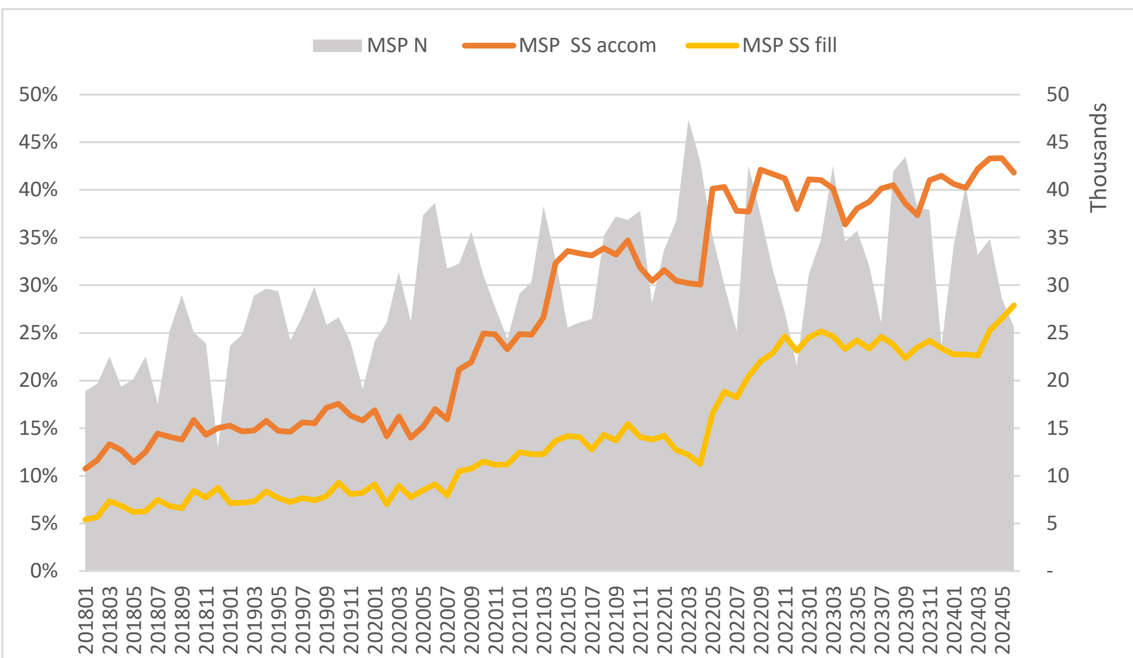
[39] G-Army was changed to allow high priority reservations to generate a PR even if there was a low priority due in (e.g., a stock replenishment). This change was made because low priority PRs are translated to low priority purchase orders (POs) which are more likely to get backordered at the national level. Hence, without this change, a high priority reservation needed to complete a workorder on non-mission capable (NMC) equipment could be waiting on a due in from a low priority stock replenishment that is backordered at the national level.

Figure 4.5. Class IX Performance Across All Ground BCTs



SOURCE: RAND Arroyo Center analysis of GCSS-A data.
NOTES: Class IX N = number of class IX part reservations; SS accom = shop stock accommodation; SS fill = shop stock fill rate.

Figure 4.6. MSP Performance Across All Ground BCTs



SOURCE: RAND Arroyo Center analysis of GCSS-A data.
NOTES: MSP = maintenance significant part; MSP N = number of MSP part reservations; SS accom = shop stock accommodation; SS fill = shop stock fill rate.

Chapter 5. Conclusion

The benefits of pooling demands across units supporting like equipment and changing to a mathematical optimization approach to setting inventory levels in Army shops led to significant performance improvements. Tracking metrics and simulation results suggest that more performance improvements are possible if units can fund (i.e., turn on replenishment) of CSSL inventory levels. If funds are problematic, units could turn on replenishment selectively focusing on the lower cost items (80 percent of the lowest cost parts on a typical CSSLs account for just 20 percent of the overall CSSL value). Also, further improvements in part availability can be had at very little additional inventory investment and storage space by extending the CSSLs to include bench stock items. Further performance improvements may also be possible if plant 2000 inventory accuracy were improved.[40]

In this project CSSLs were computed for ground BCTs. Because the ground BCTs have many like units (shops that support same/similar equipment), this analysis has shown there is significant benefit to pooling demand and moving from a two-step heuristic process to mathematical programming. However, these benefits are not limited to the Army's ground BCTs. The same concepts and potential benefits would apply to any BN or CO unit that maintains an SSL (the more like units, the greater the benefit from pooling the demand histories).

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[40] See James R. Broyles, Ken Girardini, Andrea M. Abler, Candice Miller, Jason Mastbaum, Peter Schirmer, Erin N. Leidy, Sam Morales, Aimee Bower, *Advancing Army Logistics Data Quality Process Improvements and Metrics*, RAND Corporation, RR-A1953-1, 2024.

Appendix A. Definition of Bench Stock Versus Shop Stock

The initial CSSL runs were made using all part reservations with a combined line constraint of 500 lines. The sponsor and stakeholders decided that the CSSL effort would only be for parts that qualified for shop stock, and that parts that qualified for bench stock would not be included in the implementation. As a result, a definition of bench stock items was generated to differentiate the shop and bench stock items. Army policy AR710-2 provides some guidance for defining bench stock. However, the criteria are not overly prescriptive, and the research team determined there was significant variation across maintenance shops (e.g., the same part would be coded as bench stock in one shop and as shop stock in another shop). The only way to determine if an item was considered bench stock was for an inventory level (either a SS or an ROP) to be set in GCSS-A with the bench stock indicator set. However, as pointed out 40 percent of the shops we analyzed had less than ten lines with inventory levels – so it was not clear which items were considered bench stock in such shops. Also, some units had vendor replenished bench stocks that were being managed outside GCSS-A. All this complicated how to differentiate between bench and shop stock.

As our analysis was limited to class IX (repair parts) we used the applicable criteria from AR710-2:

- Accounting requirements code (ARC) = X (the part is expendable)
- Return code (RC) = Z (the part is a non-reparable/consumable)
- CIIC = U for SC = 9M (Repair Parts - Weapons - small arms, rocket launchers, machine guns, etc.)
- Controlled item inventory code (CIIC) = U (unclassified) or J (pilferable) for supply class (SC) ≠ 9M

The above criteria still allow most class IX repair parts (except reparable parts). AR710-2 also states: "Bench stocks are **low** cost, high use, consumable Class 2, 3 (packaged), 4 and 9 (less components) items used by maintenance personnel at an unpredictable rate. Bench stocks consist of common hardware, resistors, transistors, capacitors, wire, tubing, hose, ropes, webbing, thread, welding rods, sandpaper, gasket materiel, sheet metal, seals, oils, grease, and repair kits."

With input from SMEs we added additional criteria based on the unit price and the unit cube. These criteria reflect the different units of measure sometimes used in plant 2001 (SSAs) and plant 2000 (shops). For example, the SSA may issue a single box of 100 washers. The unit of measure at the SSA is unit of issue (UoI) of one box and UoI is reflected in the catalogue unit price (cost of a box of washers) and unit cube (the cube of the box). In the shop, the unit of measure is base unit of measure (BUM). So, the shop quantity would reflect 100 washers and would issue or consume the washers one at a time.[41] The quantity of washers in the box is referred to as the conversion factor (CONV) or rounding value in the GCSS-A data fields. The criteria were:

- The unit cube must be ≤ 0.2 cubic feet (implies UoI of an item should be able to be placed in a typical bin location).
- The unit price of the item ≤ \$40 OR the price in BUM = unit price/CONV ≤ \$5

[41] For bench stock often the box of washers would be emptied into a bin on the shop floor so they are available to technicians and clerks would periodically inspect the bin and order another box if the on hand level was judged to be low.

Abbreviations

ABCT	armored brigade combat team
AMI	Army-managed item
AR CO	Armor company
BCT	brigade combat team
BN	battalion
CASL	common authorized stockage list
CSSL	common shop stock list
CO	company
FR	fill rate
FSC	forward support company
GCSS-A	Global Combat Support System—Army
HMMWV	high-mobility multipurpose wheeled vehicle
IBCT	infantry brigade combat team
MIP	mixed-integer programming
MRP	material resource planning
MSP	maintenance-significant part
NAMI	non-Army-managed item
OH	on hand
OPTEMPO	operational tempo
RO	requirement objective
ROP	reorder point
SBCT	Stryker brigade combat team
SLOC	storage location
SME	subject matter expert
SS	safety stock
SSL	shop stock list
SSA	Supply Support Activity

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