Holding every spare part needed when and where required will never be efficient or affordable.

There are many metrics of spares availability, but System A_0 is the most important. Optimized inventory should deliver '*Happy Systems*' not just '*Happy Shelves*'.

Required spares stocks are defined by the Range and Scale by location.

Spares provisioning requires both Initial Provisioning (IP) and Re-Provisioning (RP).

There are 2 principle spares provisioning methods: Single-Item Modelling that assesses each item in isolation and ignores its cost; and Availability-based system modelling that assesses all items simultaneously using its costed-weighted contribution to A_0 using a Marginal Analysis Technique.

Availability-based system modelling costs are typically 50% of the cost of engineering judgement and 25-33% cheaper than Single-Item Modelling.

Automated Re-Provisioning systems use Single-Item Modelling methods and erode the initial benefit from Availability-based IP. Given the potential waste, Availability-based Modelling should be used for RP through-life.

Providing spares does not deliver effective support since maintenance activity also requires other resources, such as skilled people, tools, test equipment, facilities, documentation etc. Multi-resource optimization is necessary.

Optimised Inventory Management

Having every spare part available immediately when and where required will almost certainly be excessively costly and unaffordable. Therefore, optimizing the inventory of spare parts at each location is a major objective of supportability analysis to maximize system availability for the lowest cost investment

System Availability

While spares availability is important, holding inventory has a cost to acquire, store and manage; it may also require periodic in-storage maintenance even if it is not used. Therefore, stock levels should be justified for their contribution to system availability and not as an end in themselves. For example, because components have different failure rates, it might be more cost-effective to hold 2 items of an unreliable component, but none of a more reliable one rather than stocking one of each.

Optimised inventory should deliver **'*Happy Systems'*** not just **'*Happy Shelves*'**. Overstocked shelves may provide subjective comfort to logisticians, and a good source of income for suppliers, but are wasteful. The most common metric is A_0, which measures the operational availability of the system.

Spares Availability Metrics

Inventory optimization ensures that the correct items are available in the correct location when needed for the available budget. The graph in Figure 23-1 below shows the generic relationship between system A_0, Fill Rate and Delay Time. Increasing investment improves the spares satisfaction fill rate which delivers more system availability and similarly reduces the average delay time.

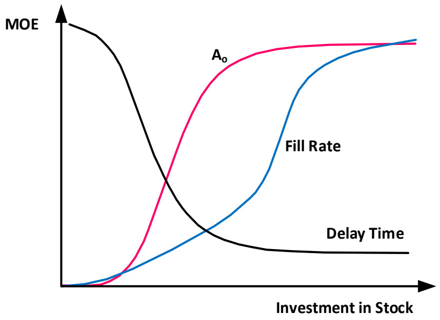

Figure 23-1: Relationship between System Availability, Fill Rate and Delay Time

There are many specific metrics of spares availability. Off-the Shelf Satisfaction Rate (OSSR) reflects the proportion of demanded items that are immediately available. Overall Satisfaction Rate (OSR) measures the proportion of items that are available, but not necessarily in the right location. OSSR and OSR are both Fill Rates which describe the confidence of having a part available when required.

Spares that are not available result in Back Orders (BO) on manufacturers, which implies delay. Cannibalization is a temporary local tactical expedient to manage urgent supply shortfalls; ideally, this should be eliminated, but that would be unrealistic and excessively expensive.

To preserve system availability, the number of spares held as stock must be sufficient to cover the time taken to replenish the stock with a serviceable item. The main drivers are the failure rates, the RTRT if appropriate, and both the purchase and repair costs. Reducing repair turn-round and replenishment times will minimize the need to hold spares stock to cover the pipeline time. Holding more stock increases the probability of having a specific spare available when required. This approach ignores the time to return unserviceable items for repair and assumes that infinite stock is available somewhere subject to delivery delay.

Spares Provisioning and Management

The purpose of spares provisioning and management is to make available the spares that maximize A_o for an affordable cost or that minimizes the cost for a required A_o. To preserve system availability, the spares stock must be adequate to cover the time taken to replenish the stock with a serviceable item either by repair or as a new buy. The BOM is the list of all physical items that comprise a system.

- The **Range** is the list of items that are held as spare parts.
- The **Scale** is the number of items held at each location.

Not all items in the BOM should be provisioned as spares, not all the Range will be held in each location and scales of zero are valid.

Provisioning is the process of identifying the required Range and Scales of spares and ensuring that they are sustained.

- Initial Provisioning (IP)

  IP is conducted to define the initial spares scales for the initial in-service period; this is typically 2 years. Early in the life cycle, historic evidence of demand rates is often unavailable, IP is based on the best available predictions of failure modes and rates. However, these failure estimates can be erroneous, creating spares shortages or excesses which need to be resolved.

  IP for large systems is often divided into a number of Initial Provisioning Lists (IPL), of which the first provides data for the Long Lead Time Items. Equipment can be presented in IPL by sub-system or supplier, and it is normal for these to be in descending purchase lead time to enable order administration and delivery ahead of the Logistics Support Date.

  The content of IP is normally restricted to LRUs and Special-to-Type Test Equipment (STTTE) specific to the new equipment. Items that are common to Systems already in-service and normally procured through existing supply management, although those requirements need to be quantified and orders placed.

Integration of IP data and illustrations is a key aspect of the introductory process, and this data should form the data modules for the Illustrated Parts Catalogue (IPC) within the Technical Publications or Interactive Electronic Technical Publications (IETP).

Because IP is nearly always conducted with uncertain data, initial Scales will always be wrong to some degree. Therefore, rather than commit all of the available IP cash to order the full optimum Scale, it would be prudent to preserve some budget flexibility to deal with the inevitable consequences of the different actual data. Items that will require overhaul in some years' time may not appear in early data gathering but will need investment in due course and often have long lead time.

Moreover, factors (such as reliability, prices and user demand) will change through-life. Therefore, optimal IP will never be sufficient, and the inventory must be actively managed through life to sustain, improve and mitigate any deterioration in spares performance.

- Re-provisioning (RP)

  IP is only intended to establish sufficient stock to prime the pipeline with repairable items and, for consumables, to provide sufficient stock to allow RP processes to take effect.

  Once in-service experience generates reasonable failure data, RP uses historic consumption trends as the best indication of future need to refine the initial spares estimations to more accurately reflect the future pattern of system failure and spares demand. Whenever the system configuration is modified or upgraded, the provisioning calculations should be revisited using the best available data. Similarly, any changes to the operating pattern or support arrangements must be assessed and the impacts reflected in adjustments to the scales.

- Stock Replenishment

  Stock replenishment is a key factor in RP. The number of spares consumed in a period is defined by the rate of use of the system and item reliability. Spares must be reordered sufficiently early to avoid replenishing the stock before it runs out given the procurement lead time. The number ordered will be defined by the economic order quantity. This leads to a saw-tooth pattern of stock holding as illustrated in Figure 23-2 below. As there will be some random variation in demand rates, it is prudent to calculate the safety stock to retain a margin of a minimum planned stock level to cope with unusual peaks of high demand or variation in PLT.

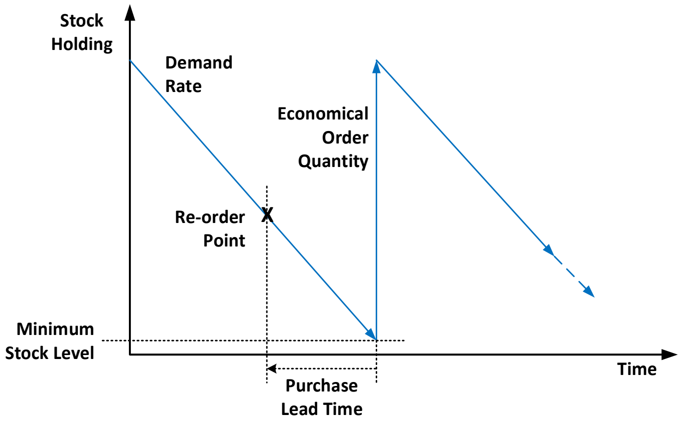

Figure 23-2: Spares Re-order Points

Spares Provisioning Methods

There are 2 principal methods for spares modelling:

- Single-Item Modelling assesses each item in the range independently. Consequently, the cost of each item is not a factor in determining the number required and is not a discriminant on the most effective expenditure of the support budget.

- Availability-based system scaling, also known as Multi-Indenture[1] Multi-Echelon[2] (MIME), assesses all the items in the system simultaneously to identify and select those which provide the greatest contribution to overall system availability for the least cost. MIME reflects the complex environments where spares are required at multiple locations with partial or full repairs at various levels.

  Availability-based system scaling must be based on detailed knowledge of the system EBS, the operational significance of each part in the structure, the equipment attributes (such as reliability of each part in each location in the structure) and, most importantly, the costs which become a discriminant.

Single-Item Modelling (SIM)

SIM assesses each item in the range independently. Typical measures of SIM performance are OSSR and OSR which, in effect, describe the confidence of having a part available when required. These measures are also called Fill Rates. Holding more stock increases the probability of having a spare available when required.

As failures occur randomly, the mathematical probability P(n) of having a spare available when required is[3].

$$\boldsymbol{P(n) = e^{-\lambda t}\left(1 + (\lambda t) + \frac{(\lambda t)^2}{2!} + \frac{(\lambda t)^3}{3!} + \cdots + \frac{(\lambda t)^n}{n!}.e^{-\lambda t}\right)}$$

Where:

n = number of spares held
λ = failure rate
t = time to replenish stock - pipeline time.

Availability-based System Modelling

Availability-based System Modelling uses A_0 as the measure of performance. It assesses all the items in the system simultaneously to identify and select those which provide the greatest contribution to overall system availability for the least cost. The comparative value is determined by progressively considering the individual risk of shortage for each candidate spare weighted by its cost. This can also be expressed as the number of Expected Back Orders (EBO). The initial system shortage without any spares available is 100%. By choosing to hold the spare with the largest impact on system availability, at a cost, the overall shortage or EBOs is decreased for the overall system. As the EBOs for that item is now less since some stock is available, the process is repeated to recalculate the shortage both for the overall system and for each item. This leads to a series of individual part choices that form an optimal locus of spares to achieve system availability for a specific cost until the requirement is met. This mathematical technique is called Marginal Analysis. The diagram in Figure 23-3 below illustrates the technique. By definition, it is infeasible to achieve more availability than the optimal locus while any other choice is sub-optimal, inefficient and wasteful.

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[1] Multi-Indenture reflects the system EBS such as system, sub-system, LRUs, SRUs and piece parts.

[2] Multi-Echelon reflects levels of repair such as User, and Levels 1-4. Equipment Maintenance Policies define which items are replaced and repaired if appropriate at which levels.

[3] $P(n) = e^{-\lambda t}\left(1 + (\lambda t) + \frac{(\lambda t)^2}{2!} + \frac{(\lambda t)^3}{3!} + \cdots + \frac{(\lambda t)^n}{n!}.e^{-\lambda t}\right)$
NAVAIR 00-65-502/NAVORD OD 41146 Reliability Engineering Handbook: n = number of spares held, λ = failure rate, t = time to replenish stock (pipeline time). λt is the number of fleet failures (demands) in time taken to replenish stock.

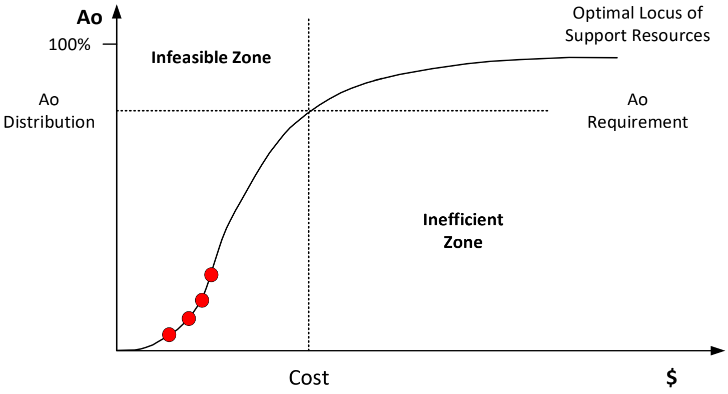


Figure 23-3: Marginal Analysis Locus of Optimum Part Choices

Confidence Limits

The achieved availability is based upon mean data, but failures are inherently stochastic with some statistical variation. Likewise, the cost elements may in practice be subject to some variability. This can be thought of as ellipses of confidence about the mean point as illustrated in Figure 23-4 below.

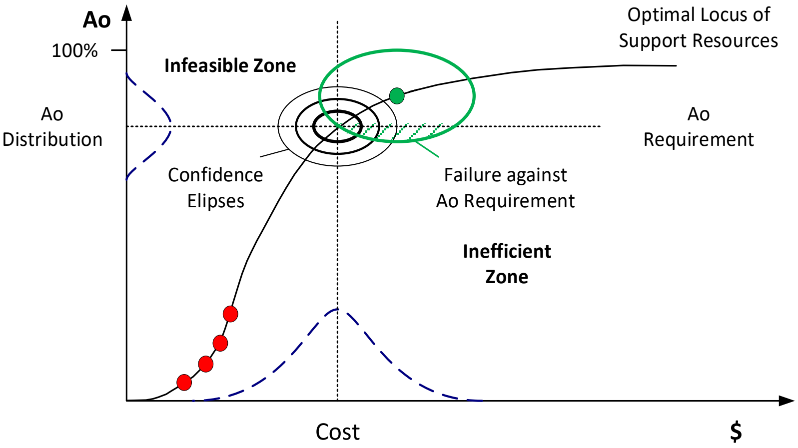


Figure 23-4: Marginal Analysis Locus of Optimum Part Choices

To ensure that the probability of failing to meet the minimum requirement is within tolerable limits, the mean point must be moved up the locus to include additional items.

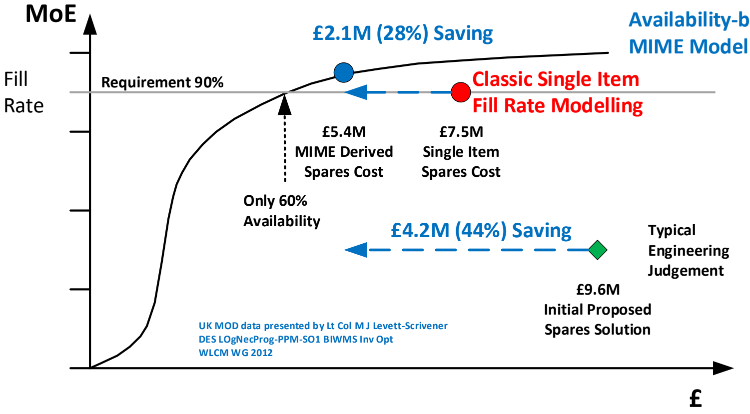
IP Approaches

There are 3 typical approaches to calculate IP stocks.

- **Engineering Judgement** based on previous experience, but this is often flawed leading to shortfalls or expensive stock holdings.
- **Single-Item Modelling** works at the item level treating each part independently. Typical measures of performance are OSSR and OSR which, in effect, describe the confidence of having a specific part available when required. These measures are also called Fill Rates. This approach can be described colloquially as ***"Happy Shelves***".
- **Availability-based System Modelling** works at system level addressing all parts simultaneously with overall system availability the key performance metric. By choosing to hold the spare with the largest impact on system availability, at a cost, the overall risk or

shortage is reduced for the overall system. MIME modelling incorporates these principles for complex environments where spares are required at multiple locations, with partial or full repairs at various levels. This approach can be described colloquially as ***"Happy Systems".***

Over many years, Engineering Judgement has proven to be least effective and most expensive. SIM is better, but for a given A_o, System-based Modelling typically produces scales that are 25-30% cheaper as illustrated below in Figure 23-5 from UK MOD data; this bears out Sherbrooke's original conclusions in his book Optimal Inventory Modelling of Systems.



UK MOD data presented by Lt Col M J Levett-Scrivener
DES LOgNecProg-PPM-SO1 BIWMS Inv Opt
WLCM WG 2012

Figure 23-5: Relative Efficiency of IP Approaches

Consumables

Low-value consumables may be an exception to the general principle that system-based modelling should always be conducted. While the lack of consumables and piece-parts can make the system unavailable, the effort to collect modelling and the additional processing time needed to run comprehensive models may outweigh the potential savings. It may be cheaper and just as effective to adopt Kanban principles of stock management to ensure that consumables and piece parts stocks are always available even if over-stocked.

Applying cost weighting to consumables may be a useful interim measure.

Automated Re-provisioning

Once initial scales are established, stock levels are normally maintained automatically by algorithms within the various inventory management and ordering systems used for RP.

For consumables, which are typically low cost, RP is a relatively simple exercise of ordering in economic quantities sufficiently early for the remaining stock to last for the procurement lead time as illustrated above. However, current RP algorithms are fundamentally SIM approaches. If these are adopted, all the benefits of adopting SIM initially for IP will be progressively eroded leading, by a reversal of the previous logic, to 25-33% more expensive and less effective solutions from SIM approaches.

A Maintenance Policy Review should be conducted regularly as suggested in Section 29 on SA, or at least before each contract re-negotiation, immediately followed by comprehensive review of in-service stock holdings using Availability-based Modelling. In many countries, this practice is not followed leading to excessive growth in unnecessary stock holdings. Industrial Primes and OEMs privately welcome the increased order flow and will not complain about the malpractice.

Because automated RP is a continuous activity without special action stock effectiveness will constantly deteriorate but will be largely unseen. Faced with other pressures, Inventory Managers do not have the capacity to conduct the necessary activity. Ideally, continuous availability-based RP should be conducted which implies an automated system.

Given the potential waste, Availability-based Modelling should be used for RP through-life.

Non-Cost Optimization

Spares packages are normally optimized for cost since that is typically the principal constraint when procuring spares resources.

In special circumstances, other metrics may be more appropriate. If storage space is the dominant constraint, as for example in a submarine, the spares package should be optimized using the packed volume of the spares. For air transport, weight may be the constraint and the optimization denominator.

TFD spares optimization tools use shadow currencies (such as cubic meters or kilograms) as optimization bases.

Multi-Resource Optimization

Inventory optimization identifies the optimum spares at each location. However, as described in Section 10, providing spares does not deliver effective support. Maintenance activity also requires other resources such as skilled people, tools, test equipment, facilities, documentation etc.

The spares optimization methodology uses marginal analysis to identify the next best part based on its contribution to reduce the EBO per unit of money expended. The same concept applies to the other resources, but with EBO replaced by ‘Waiting Time’. For example, maintainability is improved by reducing the waiting time for the associated mix of spares, tools and people for each task with each available at a specific cost.

Multi-resource optimization adopts the marginal analysis technique to allocate progressively the optimum mix of resources.