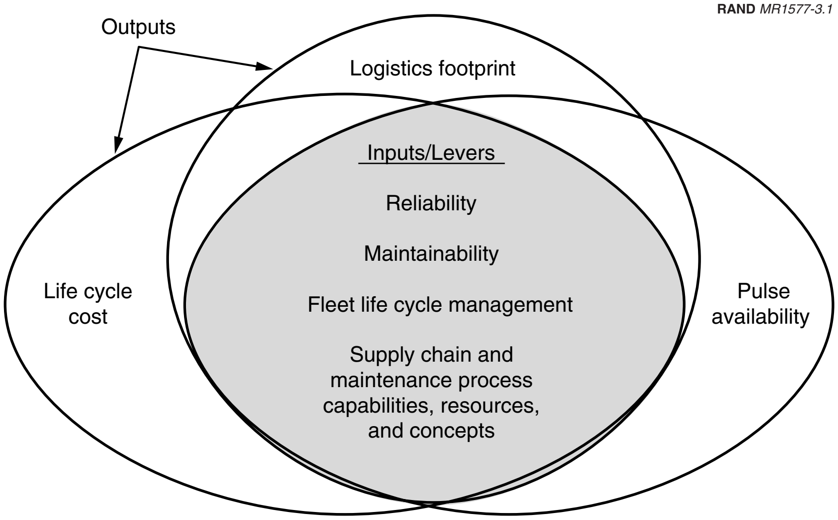
Chapter Three

HOW SHOULD EQUIPMENT SUSTAINMENT REQUIREMENTS BE DEFINED AND MEASURED?

The previous chapter described the three costs of poor sustainability. This chapter turns to a discussion of how to define requirements to improve the sustainability of future equipment. It recommends high-level equipment sustainment goals and describes how these goals should factor into the requirements and acquisition processes. Then it proposes a potential template of metrics to define and measure sustainment requirements that should be considered in all major end item acquisition programs. Finally, it examines a cross-section of Army requirements documents to assess the degree to which these requirements and metrics have been employed by the Army.

GENERAL EQUIPMENT SUSTAINMENT GOALS

The three costs reflect the three general primary reasons the Army cares about equipment sustainment. The Army wants equipment available for use when needed to accomplish missions; wants this equipment kept available with as small a maneuver force maintenance footprint as possible; and wants the maintenance of equipment to cost as little as possible. Each goal is directly affected through quantifiable relationships by the reliability and the maintainability (to include durability) of equipment; the fleet life cycle management effectiveness; the amount of supply chain and maintenance resources available; the effectiveness of the supply chain and maintenance processes; and the support concepts employed. These "levers" might be considered the inputs to equipment sustainability, with the goals representing the outputs, as depicted in Figure 3.1.



A change in any one of the inputs or "levers" is likely to impact multiple "outputs" or goals and not necessarily in the same direction

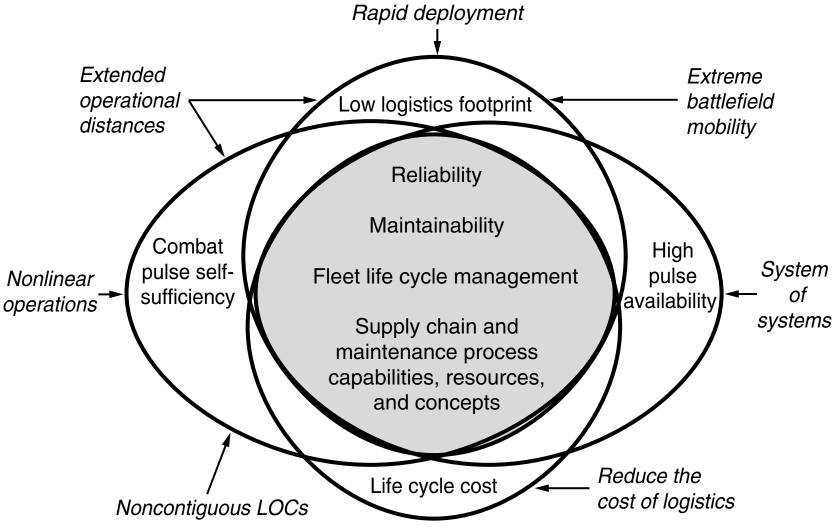
Figure 3.1—General Equipment Sustainment Levers and Goals

Depending upon the action, an improvement in one of these levers could positively affect all three higher-level goals, but at other times a change in one may result in tradeoffs among goals. For example, more maintainers might increase availability (depending upon whether capacity is constrained or not) but would add footprint and cost. While the focus sometimes becomes more intense on one of these levers, each can play a substantial role in helping the Army reach its ultimate sustainment goals.

Tailoring Equipment Sustainment Goals to the Army Transformation

When determining equipment sustainment requirements, the Army, as with all other requirements, should tailor these general goals in accordance with the overall operational goals and the concepts that have been identified as the best approaches for achieving them. The Army has articulated overall and operational goals and concepts for the Objective Force, as arrayed around the overlapping ovals in Figure 3.2. They describe concisely how the Army intends to structure and employ its force to fight in the 2025 time frame.

These operational goals and concepts have implications for logistics and readiness that the Army has also identified and that are described in outer portions of the four overlapping ovals in Figure 3.2. As discussed previously, the desire to have a rapidly deployable force drives the need to minimize the maintenance footprint that must be deployed, and the desire for extreme operational and tactical mobility over extreme distances further demands a low maintenance footprint in the maneuver force. Combining the extended operational distances envisioned with the desire to conduct nonlinear operations with forces widely distributed across a combat zone, which will produce noncontiguous lines of communication, generates the need for



Objective Force and Transformation goals and concepts
Logistics and readiness implications → Overall equipment sustainment goals
“Levers” influencing each of the overall equipment sustainment goals

Figure 3.2—Tailoring Equipment Sustainment Goals to the Army Transformation

maneuver force self-sufficiency during what is becoming known as combat pulses. A force will move out and conduct continuous operations without external support for a given period of time (for example, three days), before it comes back to some sort of base or "plugs in" to a support unit to prepare or "refit" for another pulse. As a result of new Objective Force concepts, self-sufficiency becomes a fourth overall equipment sustainment goal beyond the three general ones identified in Figure 3.1.

The Army has always been concerned with the need to have available equipment, but, as we will discuss in more detail later, the notion of an FCS as a system of systems with strong interdependencies—which introduces network availability issues to combat forces—potentially implies higher-than-ever equipment availability requirements at the system level, depending upon how the overall network is designed. For example, in a traditional armor company of 14 tanks, one might think of the loss of one tank as the loss of one-fourteenth of its combat power; the loss of a single tank has limited effect on the value of the other 13. Compare this with a unit composed of several different types of systems, some of which depend upon others, such as indirect-fire systems depending upon unmanned aerial vehicles (UAVs) to identify and track targets. In this case, the loss of a UAV can sharply reduce the value of linked systems. (This is akin to the dependency of all the personal computers hooked to each hub or router in a local area network. If the central hub is down, this entire part of the network shuts down.) Such a system should probably have either high availability or redundancy or substitutable "nodes." The last two could lessen the stringency of equipment availability requirements for individual pieces of equipment or even make a system more robust.

The need for higher pulse availability at the platform level is increasingly becoming recognized as critical to FCS development. Initially, the Army was more focused on achieving high or "ultra" reliability at the platform level. As will be discussed further, this is just one means, albeit an important one, of achieving high availability at the platform level, which is just one means of achieving high network availability.

Finally, the Army and DoD have been increasing the emphasis on the life cycle cost of programs over the last few years as they have come to understand that the bulk of life cycle cost comes not from acquisition, but from operating and support costs. By acquisition policy, life cycle cost must be tracked and targeted in all programs.

MEANS FOR ACHIEVING EQUIPMENT SUSTAINMENT GOALS

To support Army Transformation, within the categories presented in the middle of Figure 3.2, the CSS community has begun to determine the concepts to be employed and the principles to be followed in the creation of CSS structure, CSS doctrine, and equipment design to meet Army Transformation goals and to support Objective Force operational concepts. For instance, through better reliability and maintainability (e.g., prognostic capabilities), the Army will be able to reduce critical failures during combat pulses both because there will be fewer failures and because it will be far better able to anticipate the remaining failures and replace soon-to-fail components before commencing operations. Better maintainability can also reduce downtime and resource requirements when failures do occur, and it could facilitate the ability of operators and crews to take on greater maintenance responsibility, thereby reducing footprint. Increasing platform commonality can improve supply support for a given level of investment and footprint. Successfully employing these concepts and principles becomes the objective of CSS system and weapon system design. To the extent that weapon system design and program requirements can help achieve these objectives, they should be emphasized in operational requirements. Other objectives, such as those involving spare parts distribution, are broader in scope than any one program and will be driven primarily by efforts outside of weapon system procurement.

Consistent with the Objective Force–derived logistics and readiness goals, the Army has developed aggressive CSS Transformation goals with regard to increasing deployment speed, reducing CSS footprint, and reducing the cost of logistics. It has been recognized that these aggressive goals probably cannot be achieved solely through changes in logistics structure and processes. In conjunction with these changes, it is also essential to change radically the nature and number of demands that the Army's equipment places on the logistics system. Therefore, the acquisition process must play a key role in achieving not just Army Transformation and Objective Force operational goals, but also CSS Transformation goals.

Nothing that the Army is talking about with regard to improving equipment sustainability is fundamentally new from a functional design standpoint. Also not new is the ultimate purpose of equipment sustainment—the ability to provide and sustain combat power during operations—or the types of costs it imposes. What are new are the objectives for the overall requirements, which are unprecedented in their demands (due to unprecedented operational demands). What are also new are some of the assumed constraints (e.g., combat pulse self-sufficiency).

THE ROLES OF OVERALL GOALS AND FUNCTIONAL DESIGN REQUIREMENTS

In the framework just discussed, two types of equipment sustainment requirements begin to emerge for the development of the Army's Objective Force. The first type consists of overarching equipment sustainment goals driven by overall Army operational and cost goals that represent composite measures of logistics system and equipment design parameters. They are

- High pulse availability.
- Low maintenance footprint.
- Combat pulse self-sufficiency.
- Low life cycle equipment sustainment cost.

DoD acquisition policy has been increasing its emphasis on the use of broad goals such as these, because they allow flexibility in designing concepts, logistics processes, fleet management strategies, and equipment that will meet operational needs. In short, they enable effective use of tradeoffs. By providing the freedom to find the best way to improve performance, they foster innovation and empower suppliers by keeping options open.

However, performance against these overarching goals is often not measurable and is often beyond the scope of responsibility of one organization; rather, overarching measures of performance are functions of many design elements. Instead, one-dimensional, functional requirements that can be directly aligned with design characteristics and directly measured facilitate successful program management, which requires the achievement of a specified level of performance, on time, and within budget. Clear, precisely measurable metrics that are narrowly defined along functional lines allow performance feedback and accountability throughout a program. Their use enables program management to monitor performance along each design dimension before the full system has to come together. In addition, if a shortfall occurs with regard to an overarching goal, having measures for each of its component design characteristics will help isolate the source of the shortfall and facilitate the identification of ways to fix it.

The broad, overarching goals and the metrics selected to communicate performance against these goals should be oriented toward developing concepts and then selecting the preferred concept. Once the final concept is selected, detailed requirements can then be specified based on the conceptual design. The use of detailed requirements is necessary to ensure that the Army gets what it has been promised. However, if these detailed requirements are specified too soon in a new weapon system program, the Army runs the danger of prematurely eliminating a better overall solution set. *In other words, the selected concept represents a promise to achieve the overall goals based on a set of design assumptions. The role of the detailed requirements is to ensure that these assumptions are met so that the overall goals are achieved.* Thus, the two types of requirements are complementary. Each overarching goal is a composite one that is a function of several one-dimensional functional requirements and the environment in which the equipment will be employed (e.g., operating concepts and mission profiles).

The Evolution of Requirements

When an acquisition program starts, as long as there are competing concepts, it is undesirable to define the entire set of equipment sustainment requirements in precise detail, particularly those oriented to one-dimensional functional design objectives. Instead, during concept exploration, the Army should first assess how the mission need influences the importance of each of the overall equipment sustainment goals; it may become apparent that multiple goals, such as footprint and availability, have unusually high importance to a program. For example, an item that deploys forward should have a smaller local maintenance footprint in order to be mobile than one that operates from the rear. Or it could be determined that there is a hard constraint for one of the goals. For example, a deployment analysis might show that the maintenance footprint has to be less than or equal to some value. From this examination, high-level goals should be set in terms of availability, footprint, life cycle cost, and self-sufficiency. Understanding the balance needed in a program as well as the desire for the absolute levels of each goal should then drive the means, in other words the design features, that receive the most emphasis as contractors perform concept and technology development.

As concept and technology development and assessments evolve, the program and each concept team should start generating estimates of feasible ranges of reliability and maintainability and the risks associated with relying on various levels of performance along these and other dimensions. Based on these estimates, the program can assess the feasible levels of each overall goal that could reasonably be achieved through different combinations of reliability, maintainability, fleet life cycle management plans, and supply chain support. Each estimated potential level for an overall goal would carry a level of risk derived from the risks associated with achieving the related, functional design objectives. Each such combination of levels of the functional design objectives comprises an alternative concept, as illustrated by the three concepts on the left side of Figure 3.3. Finally, through joint consideration of the overall goals, the Army has to compare the overall value and risk of each concept and then decide which to pursue.

Once a concept is selected, typically at Milestone B of the acquisition process, the design assumptions upon which the expected performance of this concept rest should become the detailed program requirements, as seen in the figure. At this point, the requirements should be fully specified for Operational Requirements Document (ORD) validation. In cases where the Army or DoD elects to continue competition past Milestone B through multiple development efforts, then the detailed requirements derivation should be delayed until the program selects one concept.

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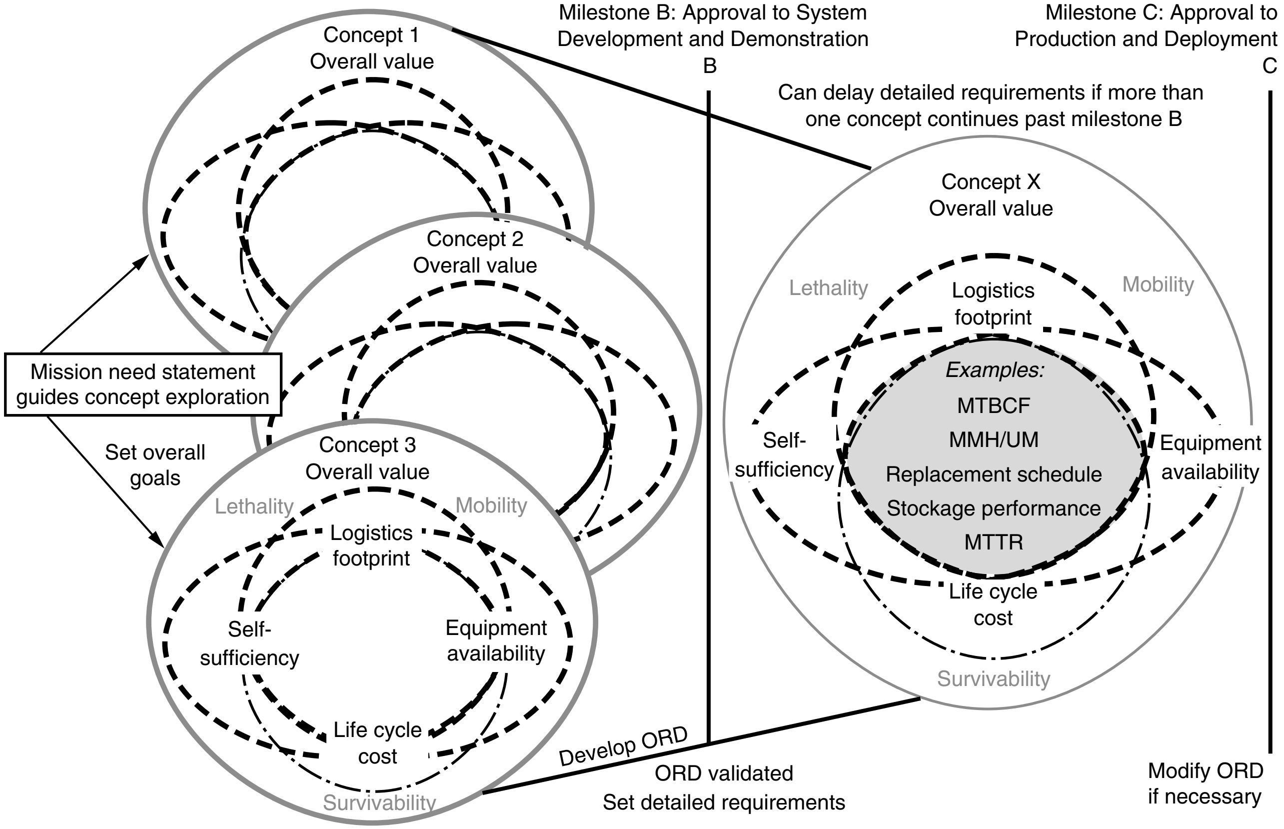

Figure 3.3—The Evolution of Program Requirements

As concept and technology development progresses, a broad tradespace bounded and guided by the mission need statement should gradually narrow until it collapses on a solution set when one concept is selected. In the first iteration of requirements determination for inclusion in an initial ORD, targets for each of the overall goals should be determined. These include pulse operational availability, life cycle cost, self-sufficiency (if applicable), and maintenance footprint. Concept exploration determines the best way (i.e., mix of reliability and maintainability initiatives, supply chain support, life cycle planning, etc.) to achieve these objectives, and then the resulting solution set becomes the operational requirements in the validated ORD. The large trades will have been made by this point, and the "official" tradespace exists between the threshold and objective for each requirement. An unofficial tradespace, though, extends beyond the thresholds for non-KPP requirements. (Chapter Five's discussion of KPPs compares the "power" of thresholds for KPP and non-KPP designated requirements.) Tradeoffs beyond the thresholds are likely to be "negative" in nature, barring unexpected technological breakthroughs. For example, it may be found to be infeasible to achieve the reliability target. Then a decision has to be made with regard to either relaxing the pulse operational availability (A_o) requirement or achieving it by adding more logistics resources, which would increase footprint and cost.

Program and Contract Scope Considerations Drive the Need for Detailed Requirements

If a contract is to be sufficiently broad, then it may not be necessary to determine and specify detailed requirements. Rather, if contractors have a sufficiently broad scope of work in which they control all the necessary levers, they could retain flexibility to find the best way to meet the overall goals throughout the program. There has probably not been any program in the past for which this approach would have been applicable. However, there seems to be increasing discussion of innovative approaches to weapon system contracting, such as buying "power by the hour" or even lease-use agreements, which would imply a broad scope of contractor logistics support. Such programs could simply specify, for example, an availability-oriented requirement, a deployed maintenance footprint requirement, and cost requirements (as well as pulse self-sufficiency as applicable).

When a program scope encompasses the responsibility of more than one organization, as they typically do, then the detailed, functional requirements are necessary to align requirements with each organization's scope of responsibility. The program should still retain the overall requirements. It becomes the program responsibility to manage these by ensuring that the responsible organizations all meet their functional requirements and leveraging the tradespace when shortfalls do occur. For instance, reliability and maintainability would usually be within the scope of a weapon system contractor, while spare parts provisioning and overhaul/recapitalization planning would be the responsibility of the Army. Achieving or resourcing all of these requirements would be necessary to reach the pulse A_o requirement, but this is a program requirement, and not the responsibility of either the contractor or the organizations that provide spare parts and overhaul.

Time-Phased, Evolutionary Requirements

During concept exploration, it may be determined that emerging technologies or other concepts could lead to better performance but that they will not be mature by the desired initial fielding date. Or in today's climate of rapidly advancing technology, new developments may materialize after the ORD is finalized. Such capabilities may be targeted for inclusion in subsequent fielding blocks to achieve a full operational capability in the time-phased approach advocated by DoD acquisition policy. This time-phased approach enables more evolutionary or iterative development that prevents a weapon system from becoming locked into aging technology.

EQUIPMENT SUSTAINMENT REQUIREMENTS FOR THE ARMY

We now turn to how the overall and design equipment sustainment requirements should be defined and measured. The list of requirements in Tables 3.1 and 3.2 provides a recommended starting point for the development of a standard set of equipment sustainment requirements and associated metrics that all programs should con-

Table 3.1

Equipment Sustainment Overall Goals and Metrics

Requirement Category	Equipment Sustainment Program Goals	Potential Standard Metrics for Defining Sustainment Requirements
Availability	• Meet mission needs • Maximize pulse availability • Maximize sortie availability	• Pulse A_o (operational availability) — Use derived pulse A_i in some cases • Prob(successful sortie completion) • Specify pulse, refit, and sortie parameters[a]
Self-sufficiency	• Unit self-sufficiency during pulses	• Self-sufficiency pulse length
Equipment sustainment footprint	• Minimize deployment footprint and maneuver force footprint	• Maintainers by echelon (cost and footprint driver); may be relative or maintenance ratio by echelon • Maintenance equipment lift requirements
Life cycle equipment sustainment cost	• Minimize life cycle cost	• Total life cycle cost to "maintain" • Annual operation (cost per operating hour/mile) • Planned recapitalization • Spare parts provisioning • Investment in reliability (e.g., materiel)

[a] Critical assumptions that are necessary to determine the associated requirements.

sider for use. The list also notes certain critical assumptions for determining the thresholds and objectives for each requirement. Such a list could create common ground from which all Army materiel development proponents could work, and it would help align all programs with overall Army goals and equipment sustainment design trends. As methods for achieving the overall goals become identified as desired solutions, the Army can, where it makes sense, drive their adoption through consistent emphasis in new programs. For example, many have come to believe that a shift toward anticipa-

Table 3.2

Equipment Sustainment Functional Design Requirements and Metrics

Requirement Category	Equipment Sustainment Functional Design Objectives	Potential Standard Metrics for Defining Equipment Sustainment Requirements
Reliability	• Minimize mission-critical failures • Minimize maintenance requirements	• Standard form of MTBCF • MTBUM and MTBSM (by echelon)
Maintainability	• Prevent faults from becoming mission critical • Minimize downtime and cost • Minimize maintenance footprint and cost • Minimize maintenance footprint forward	• FFSP = Fn(FFP, FIR, FAR/NEOF Rate) • FFSD = Fn(FFD, FIR, FAR/NEOF Rate) • MTTR (by echelon) • MMH/UM (by echelon) • MMH/SM (by echelon) • Percent UM-crew, org, DS, GS
Fleet life cycle management	• Recognize life cycle costs up front • Account for life cycle operations • Sustain reliability and maintainability at necessary levels	• Specify replacement/recap/overhaul retirement schedule and methods • Use estimate of reliability degradation in requirements analysis[a]
Supply support	• Minimize CWT • Minimize cost and footprint	• Local fill rate • Battle damage parts kit • Wholesale backorder rate • Percent of parts that are unique • Number and positioning of end item “spares” • Specify ALDT assumption[a]

[a] Critical assumptions that are necessary to determine the associated requirements.

tory maintenance enabled by prognostic capabilities is essential to achieve reduced maneuver force maintenance footprint yet still maintain a high level of equipment availability. If prognostics or any other design feature, such as automated diagnostics that enable increased crew maintenance, is truly an essential enabler of achieving transformation goals, then the Army should ensure that each program works toward achieving the needed capability. A standard set of requirements would be useful to the Army in its quest to transform and move toward radically new concepts for deployment and operations—concepts that require dramatic reductions in maintenance footprint while maintaining high levels of force capability.

Not all of the requirements apply to all programs. In general, the larger and more significant a program is to the Army's future, the more the program will be able to influence the entire spectrum of requirements, and thus it becomes more feasible to employ a broad spectrum of these requirements. At the other extreme, a nondevelopmental program will have very little influence over many of these requirements, and thus few will make sense for a program to use.

To develop this standard set of equipment sustainment requirements, we start with the overall equipment sustainment goals presented previously in Figure 3.2 that flow from overall operational objectives and concepts. In the list, we divide the equipment sustainment requirements into categories based on the overall goals and the various levers for achieving them. Then, for each category we list metrics that would effectively measure performance against desired capabilities. Table 3.1 describes requirements and metrics for the overall goals, and Table 3.2 lists the functional design requirements—root-level measures that together determine performance against the overall goals. These are requirements that product engineers and logistics system designers can directly affect. The next two sections of this chapter explain the requirements and metrics in detail, and Appendix F provides a metrics template guide to include definitions, important considerations, how each metric provides value, and assumptions.

OVERALL GOALS

Availability

To reflect the ability to keep equipment available for use during combat or other operations—the ultimate purpose of equipment sustainment—the use of the metric "pulse A_o" is suggested. Pulse A_o is defined in this document as the percentage of time a system is available over the course of a combat pulse, which is equivalent to the probability that the system is operational at any point in time during a pulse. An alternative form of a pulse A_o requirement would be to specify a probability of maintaining a minimum A_o over the course of an entire combat pulse for a unit—call this minimum pulse A_o. This would be important when a minimum level is deemed necessary to maintain a unit's combat effectiveness. Pulse A_o, in one or both of these forms, is what the operator cares about.

It is affected by the initial availability when the pulse starts, mission-critical failures that occur during the pulse, and the ability of the logistics system (including the crew) to return NMC items to mission-capable status during the pulse. In support of determining pulse A_o from functional design objectives such as reliability, the ORD should reference the pulse length, the operating profile, and the refit period from the operational mode summary/mission profile (OMS/MP).[1] Although minimizing cost and footprint are also overall goals, they can be thought of as the negative consequences of what it takes to keep equipment operational. Each functional design requirement is oriented to maximizing A_o while minimizing footprint and cost and maintaining pulse self-sufficiency.

Since pulse A_o is defined in terms of a combat pulse, it should not be affected by scheduled maintenance, which should be executed before operations or during refit periods, or noncritical maintenance actions, which can be deferred.[2] Thus, it can be defined as

$$\frac{MTBCF}{MTBCF + MDTp}$$

(assuming initial A_o is 100 percent), where *MTBCF* is the mean time between critical failures and *MDTp* is the mean downtime per failure during the combat pulse.[3] However, as we will discuss later, *MDTp*

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[1] A refit period is a new concept being considered for the Objective Force sustainment concept in conjunction with operational pulses. Self-sufficient pulses would be followed by "refit" periods in which forces would rest, recover, and resupply to prepare for another pulse.

[2] Noncritical maintenance actions or faults are those that do not make the system unsafe to use and that do not affect mission capability, such as a bent fender or the first loss of a redundant set of parts that provide an essential capability.

[3] If a minimum pulse A_o requirement were used instead of an average pulse A_o, simulation rather than an equation would have to be used to determine the minimum

or the average total broke-to-fix time may be beyond the scope of the system developer's work. In cases where the developer is only responsible for designing the maintainability of the system to achieve a required mean time to repair (MTTR) rather than having the ability to affect the entire down time period,[4] the program could focus on pulse A_o but from it derive a required pulse inherent availability, pulse A_i, defined as

$$\frac{MTBCF}{MTBCF + MTTRp},$$

where *MTTRp* is the MTTR for mission-critical failures during combat pulses. Or the program could still specify an A_o but also specify the assumption for the administrative lead time (ALDT) during combat pulses, defined as $MDTp - MTTRp$. In either scenario, the program and internal DoD logistics providers would then be responsible for ensuring that the logistics system could meet the ALDT assumption. In cases with a very broad scope of work—in which the developer is responsible for spare parts planning or total logistics support as well as equipment design—then it could be reasonable to directly specify pulse A_o as a requirement intended to become a contractual design specification.

The critical failures that ultimately drive pulse A_o are not due to equipment breakdown or reliability alone; they may also include battle damage. However, the focus should initially be on ensuring that equipment supportability and logistics capability requirements are met—that these aspects of the design and development process are executed well. Thus the metrics used in the pulse A_o equations in this section only reflect reliability failures, not combat damage. Later in the development process, operational evaluations can pull together survivability and equipment sustainability as part of the

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pulse A_o at a given level of confidence. Even with an average pulse A_o requirement, though, the use of a simulation as described in the next chapter of this report and in Appendix A would be useful.

[4] MTTR is defined as the "clock" time it takes a repairer to diagnose faults and complete the repair, assuming all the necessary diagnostic equipment and parts are available. It is sometimes known as "wrench-turning time."

overall system and force effectiveness evaluations.[5] Sensitivity of the overall pulse A_o (including combat damage) to a range of combat damage assumptions can be explored to help assess the overall effectiveness. Such sensitivity analysis is necessary because combat damage varies greatly depending upon the specifics of the combat situation.

Another potential way to treat the issue of combat damage would be to provide a “cushion” for some level of anticipated combat damage when determining the required pulse A_o (without combat damage) targets. Alternatively, the full definition of A_o with combat damage could be employed in conjunction with an assumption for MTBCCD. Either route would produce more aggressive equipment sustainment requirements. However, given the uncertainty of combat damage rates, the meaningfulness of these approaches is likely to be low, and any derived requirements would be extraordinarily easy to challenge. Thus, the current Army practice of not including estimates of combat damage rates when determining A_o targets should continue.

Within the category of availability, the list in Table 3.1 includes one overall goal that has not been previously discussed—sortie reliability—which also relates directly to mission needs. Sortie reliability is the probability that an item will be able to execute an intended sortie or mission task (from a maintenance standpoint). Will a missile complete its flight without malfunctioning? Can a helicopter reach and attack a target without breaking down? Can a tank cross the line of departure and assault an enemy position without experiencing a critical operating failure? Sortie reliability becomes important when looking at a period in which reliability is the primary equipment

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[5] When assessing overall pulse A_o, including equipment sustainability and survivability, a broader analysis of pulse A_o would incorporate combat damage and the definition would expand to $\frac{MTBCF + MTBCCD}{MTBCF + MDTp + MTBCCD + MDTcd}$ (assuming initial A_o is 100 percent), where *MTBCF* is the mean time between critical failures, *MTBCCD* is mean time between critical combat damage events, *MDTp* is the mean downtime per failure during the combat pulse, and *MDTcd* is the mean downtime per critical combat damage event during the pulse. *MTBCF* and *MTBCCD* can be combined in a metric called mean time between critical downing events. Once equipment sustainability is well understood, a range of assumptions with regard to combat damage can be applied to evaluate the ability of the system to cope with both equipment failure and combat damage.

sustainment factor that affects mission success. The determination of sortie reliability is based upon those failures that cannot be repaired in time to complete a sortie or mission task once it has been initiated. Thus, maintainability features that allow a system to continue on a mission without "losing stride" (e.g., resetting a computer after a software failure as a tank continues maneuvering with its platoon) can also affect sortie reliability. In other words, this metric is concerned with those failures for which there is absolutely no possibility of completing repair in time to affect sortie or mission task success. As inherent reliability decreases or this period increases, this metric becomes more important. If one were to conclude that absolutely no repair was possible during several consecutive sorties or tasks that occur over the course of a combat pulse, then one might think about pulse reliability or the probability that a system could complete a combat pulse without failure.

Sortie and pulse reliability are overall goals for two reasons: They directly interest the operator, and they are not metrics posed solely in equipment design terms. They are a function of five elements: MTBCF, the length of the sortie or pulse, the operating profile during the sortie or pulse, quick fault-correction capability, and the ability to anticipate and correct probable faults before the sortie or pulse. Of these five, MTBCF and the two maintainability elements (quick fault-correction capability and the ability to predict faults) are one-dimensional functional design requirements. The other two, sortie or pulse length and the operating profile, should be specified assumptions used to determine the sortie or pulse reliability requirement and should be referenced in the ORD. These profiles are currently provided in the OMS/MP.

Objective Force concepts envision combat pulses followed by refit periods during which units would prepare for another combat pulse. Refit activities could include deferred repair of failures or combat damage that occurred during pulses (though evacuation may not occur and supplies may not be shipped forward to maneuver forces during combat pulses, information about part and maintenance requirements should flow to the necessary providers to facilitate refit preparation), anticipatory maintenance based on predicted failures, scheduled services, and possibly some recovery of assets left behind on the battlefield. The length of the refit period will be an important parameter in determining the level of resources needed to conduct refit operations to produce a given level of availability heading into the next pulse. This affects the ability to maintain the desired level of pulse A_o over multiple pulses (which depends partly on successful accomplishment of anticipatory maintenance and services executed to standard). Rather than being a requirement, the refit length will be an assumption or input that will be a critical driver of other requirements. Thus, the assumption should be specified in the ORD to create a common understanding of what the requirements are based on and under what conditions they can reasonably be achieved.

Another critical assumption that has to be made is the degree to which broken or damaged end items will be recovered during combat pulses. What will happen to immobilized equipment that cannot be repaired by the maneuver force's organic maintenance capability? What will happen to immobilized equipment within the force's repair capability that cannot be repaired before the highly mobile force performs another extended maneuver? Will immobilized equipment be blown up in place? Will it be evacuated by like systems? If so, how will this affect combat power during pulses? Or will there be a handful of recovery vehicles? The answers to these questions could play a critical role in the benefits of refit and the type of work performed during refit. In the extreme case, refit could consist primarily of end item replacement, prognostic maintenance, services, and deferred maintenance on still-mobile equipment, with all immobilized equipment being left behind.

Self-sufficiency

In cases where it is desired that the pulse A_o be achieved without external support, self-sufficiency should be an overall goal. Self-sufficiency from a maintenance standpoint is defined as a period during which an organization will operate without any resupply of spare parts or maintenance support from units that are not part of the maneuver force. This also implies that there will not be any retrograde of broken components. The length of the period would be defined by the combat pulse length specified in the OMS/MP for the system. To achieve a desired level of A_o, self-sufficiency has implications for the required levels of reliability, maintainability, amount of spare parts, and maintenance capacity within the maneuver force.

Maintenance Footprint

From the pulse A_o requirement, refit assumptions, the self-sufficiency requirement, reliability requirements, combat damage rate assumptions, and maintainability requirements, the Army can determine the maintenance capacity in terms of personnel and equipment necessary at each echelon. Alternatively, these capacity requirements could be fixed if it is desired to constrain footprint to a certain level and then one would derive one or more of the other requirements. Two simple footprint metrics, the number of maintenance personnel and the lift requirements for equipment by echelon, should be sufficient. The number of personnel and the amount of equipment they have create demand for strategic lift, intratheater lift for nonlinear operations, and sustainment resources (water, food, fuel, food service personnel, medical personnel, force protection, etc.). An alternative metric for the personnel portion of footprint would be the maintenance ratio (MR) by echelon, where the maintenance ratio equals maintenance hours divided by operating hours. MR keeps operating hours as a variable, whereas the other two metrics require it to be fixed (i.e., use of a pulse operating hour assumption). To focus development efforts, separate metrics should track maintenance footprint requirements driven by equipment failure and those driven by combat damage.

Cost

Total life cycle cost related to equipment sustainment should include annual maintenance support costs, initial spare parts provisioning, and any planned recapitalization or overhaul costs. Support cost could be measured in terms of support cost per operating mile (hour), per round expended, or any other usage characteristic that drives the maintenance requirement for an end item. Equipment sustainment life cycle costs could also include design-driven costs where design decisions made solely to improve reliability or maintainability increase cost. This could include component or subsystem redundancy, more robust components, failure-prevention sensors, new materials, and built-in prognostic or diagnostic sensors and automation.

EQUIPMENT SUSTAINMENT FUNCTIONAL DESIGN REQUIREMENTS AND METRICS

Reliability

Reliability is critical to all four overarching goals for two reasons: its effect on a force's ability to accomplish missions and its effect on the resources, in terms of cost and footprint, required to restore and sustain weapon systems. The effect of reliability on the former can be measured in terms of MTBCF.[6] This metric should encompass inherent or true equipment failures, operational failures "induced" by operators or maintainers, and perceived but false failures. Design affects the frequency with which all three types of failures occur. When we think of design, we often think of the inherent reliability of the system, which is driven by the reliability of each component; how the components work together; and redundancy. Robust designs, though, are also less prone to operator- and maintainer-induced failures—this can be thought of as error proofing. In the design process, through an approach such as failure mode effects and criticality analysis (FMECA), the design team should identify all such potential failures and attempt to find ways to eliminate any that are critical and that have a reasonable probability of occurrence. Additionally, reliable built-in tests will minimize false failures. To an operator, when a built-in test indicates a failure and the system is thus taken off line, it is a true failure regardless of whether the system is later checked out as fully operational by maintenance. Consider a fire control failure indication: If you were a tanker, would you want to go into battle thinking your fire control computer was not working properly?[7]

While critical failures are of most interest to operators because they can affect mission accomplishment, logisticians are also concerned with noncritical failures because every type of failure produces resource demands: direct and indirect labor, spare parts, transportation, facilities, and training. Thus it is imperative to measure

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[6] In this document, a critical failure is defined as a failure that makes an end item NMC.

[7] Programs might consider the use of three or even more submetrics for MTBCF, such as MTBCF_i (inherent), MTBCF_{in} (induced), and MTBCF_f (false alarm) or false alarm rate (FAR), because they generally have different improvement paths.

mean time between maintenance actions (MTBM), which should be divided into MTBUM (unscheduled maintenance—what we think of when things break) and MTBSM (scheduled maintenance—what we think of when we bring our cars in for service or schedule a tank for overhaul), because they place different types of demands on the logistics system in terms of total resources and the ability to control when they occur. To the extent that scheduled maintenance can be smoothed, it reduces workload peaks, which can reduce the necessary maximum maintenance capacity. Scheduled maintenance also improves force design flexibility, because it can be executed by shared, nonunit resources and at the time and place of the Army's choosing. To fully understand and account for the effect of reliability on how resource requirements must be distributed across the logistics system, one needs to further divide MTBM metrics into measures by maintenance echelon.

Though not an element of reliability, maintenance actions resulting from combat damage also affect logistics resource requirements and can be measured as MTBM for combat damage (MTBMcd). Therefore, MTBMcd needs to be specified as an assumption in the equipment sustainment analysis to determine overall maintenance requirements. MTBMcd and MTBM should be analyzed separately in the equipment sustainment and survivability analyses to align metrics with development efforts.

Maintainability

Maintainability encompasses factors that affect the resources and time needed to complete repairs—including diagnosis and actual work—and capabilities that enable the logistics system to keep failures from affecting operations. Important questions are: How long does it take to do the repair work ("wrench-turning time"), on average? Are there any particularly difficult and time-consuming repairs? How much training is needed to complete repairs? What special tools and equipment are needed? The answers to these questions are affected, in part, by how components and subsystems, whichever represents the desired level of replacement, are packaged within the total system. How easy are they to get to (accessibility)? Are there any blind connections? How many and what types of fasteners are required? How heavy is each part? What special knowledge is necessary? Each of these questions must be answered from the perspective of both repairing equipment breakdowns and repairing battle damage.

Another key maintainability area is the quality of troubleshooting procedures, whether fully automated through sensors and built-in tests, completely manual using paper technical manuals, or something in between such as an expert system embedded in an electronic technical manual. How long does it take to troubleshoot problems? How successful are troubleshooting procedures the first time? Three metrics are necessary to assess the quality or effectiveness of diagnostics: fraction of faults detected (FFD) (of primary interest when evaluating automated diagnostics), fault isolation ratio (FIR)—does the procedure or automation isolate the fault to the specific item that must be replaced or repaired, and FAR—the percentage of failure indications when no failure has actually occurred. These three metrics can be combined into a composite metric—fraction of faults successfully diagnosed (FFSD) the first time. Misdiagnosis or a difficult diagnostic procedure can substantially lengthen the total downtime of a system. One or the other often drives the repair time variability, and they tend to lead to long repair actions.

Together, the workload and diagnostic factors affect maintenance man-hours per maintenance action, both unscheduled (MMH/UM) and scheduled (MMH/SM), again measured by echelon, and MTTR. Maintenance hours per event affects total resources (labor), and MTTR affects downtime duration or availability.[8] Because the maintenance demands are likely to be quite different, these metrics should be evaluated distinctly for repair actions driven by equipment failure and repair actions driven by combat damage.

Beyond affecting total force structure requirements, better maintainability can reduce footprint in the maneuver force. For example, if crews can repair a large percentage of faults, it would reduce the

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[8] Maximum time to repair (MaxTTR) is also sometimes used as a requirement. It is an indication of any particularly difficult and time-consuming maintenance actions. Such maintenance actions should trigger attempted design improvements, whether to reduce the time to repair or to enable deferral until the end of a combat pulse. Used in this way, a program could use MaxTTR as a diagnostic metric to identify outlier repairs and continually drive down MTTR.

overall need for maintainers as well as those in the maneuver force. To encourage this, a metric such as the percentage of unscheduled maintenance actions that can be accomplished by the crew could be used. Parallel metrics would be the percentage of maintenance actions that are the responsibility of each echelon. The Combined Arms Support Command and the Army's Ordnance Center and School are developing a plan for a two-level maintenance system with on-system repair forward (usually remove and replace) and off-system repair rear—even with current systems that were not necessarily designed with these concepts in mind. Expressly designing new weapon systems to take advantage of new concepts will further enhance the effectiveness and value of such concepts.

Besides reducing total workload (total footprint and costs) and affecting workload distribution (footprint distribution), maintainability can play a role in reducing mission-critical failures, thereby improving pulse A_o, through prognostic technology that makes anticipatory maintenance feasible. The Army is making strong efforts to encourage the development and use of prognostics. The benefit of prognostics, though, is limited by the percentage of faults that can be predicted. Metrics parallel to the aforementioned diagnostic metrics can help quantify the potential benefit and help drive progress in this area. They are fraction of faults predicted (FFP) along with FIR and FAR. Similar to FFSD, a composite metric defined as fraction of faults successfully predicted could also be employed.

Fleet Life Cycle Management

Fleet life cycle planning assumptions and requirements should be explicitly recognized up front in program planning and resource allocation. To compute a meaningful life cycle cost requires a reasonable, supportable estimate of life cycle length. Any needs for recapitalization or major overhaul programs based on this life cycle length and the durability of the system's components should be explicitly forecast and recognized as a program requirement. Expected degradation in system failure rates over time should be accounted for—both in evaluating life cycle cost and determining reliability requirements—based upon component wear profiles and evaluations of similar systems/technologies in service. As part of this process, the program should consider durability and life cycle maintenance tradeoffs.

Estimates of reliability degradation as it affects mission-critical failures should be used in estimating pulse A_o. For example, if the Army expects a system to be in the fleet for 15 years before it is overhauled and an item suffers a 2 percent compound annual increase in the mission-critical failure rate, then the like-new reliability should be 35 percent higher than a calculated requirement that does not account for degradation ($1.02^{15} = 1.35$). To date, however, the Army does not have supportable estimates of how failure rates and support requirements increase over time.

A companion research task in the same project for which the research in this report has been executed is to develop estimates of the effects of aging on mission-critical failure rates and resource consumption. Initial findings from this research indicate that over the first fourteen years of the life of an Abrams tank, the mission-critical failure rate increases at a compound annual rate of about 5 percent, or about a doubling in expected failures for a given level of usage and environment (the data indicate that the aging effect most likely tails off soon after this range, as many of the components that contribute to the aging effect fail and are replaced—a process called renewal).

Much of the age effect comes from increases in the failure rates of simple components with dominant failure modes associated with fatigue. Examples include fittings, hydraulic hoses, and suspension components. This produces major changes in maintenance workload requirements, if not spare parts costs, and pulse A_o capabilities. If this result continues to hold as research progresses, it would be imperative to include life expectancy considerations in program planning. These considerations might include more frequent overhauls, akin to aircraft phase maintenance, and planned recapitalization programs.

Also of value, this study identifies two other categories of components that do not contribute substantially to the aging effect but are critical from a reliability standpoint. The first category consists of components with high failure rates regardless of age, making them pulse A_o drivers throughout a tank's life. The second category is medium- or high-failure-rate components with high unit prices, making them cost drivers.

Supply Support

In general, the spare parts supply chain is thought of as a broad system designed by the Army and DoD to support all weapon systems, so it is not generally thought of as an area that should have program-specific requirements. However, some systems are so significant or important to the Army's future that they may drive the entire support structure to begin a transition toward a new support concept. Similarly, a system may represent the first in a new generation of weapon systems that will necessitate a new support concept. From this vantage point, the support structure becomes integral to the total weapon system concept, and the Army may want to include any changes to the structure that are critical to making the concept successful.

Aside from this, program requirements always rest on some assumptions, often with regard to parts support. A key element of parts support that drives much of the differences in total repair time among weapon systems and units is the local authorized stockage list (ASL) fill rate—the percentage of requests that are immediately filled from a unit's supply support activity (SSA). Programs should set local fill rate performance requirements that support any assumptions made in the requirements determination process. The goals should not be to specify which and how many of each part, but rather to set an overall performance target for the local fill rate. This approach does not dictate the means, but rather the level of support that should be provided. Similarly, a level of wholesale spare parts performance could be specified. Again, this does not specify the means, such as whether parts have to be provided through organic or contractor support, only the performance to be expected in terms of having parts available for issue when needed.

Generally, the parts on deployable ASLs are for equipment failure-driven repairs. Separate requirements should be used for "battle damage parts kits" used to supplement ASLs for deployments. Such a requirement would have to be based upon assessments made during the development process as to what noncatastrophic damage may occur that would drive types of part replacements different from those normally caused by equipment failure.

One element of weapon system design that the Army can use to reduce the resource requirements necessary to provide a given level of parts support is part commonality. Using an extreme situation as an example, if ten different vehicles in a brigade used ten different chassis without common parts, there could be ten times as many unique parts as in a situation where all ten shared a common platform. Worse, it would be hard to support any of the ten very well, because the demand density at the part level for each vehicle type would be relatively low. Investments in spare parts can be a major cost contributor. Part commonality can also affect footprint, although spares are a relatively small portion of the total footprint. To drive progress on this front, the percentage of parts that are unique to the weapon system could be used as a metric. Of course, the Army must balance parts commonality against the unique requirements of each platform, depending upon tradeoffs between performance and commonality. An example of this type of thinking can be found in the auto industry, which often tries to create common platforms to reduce procurement and assembly costs. Some companies have gotten in trouble, though, when they took this concept too far. They made so many of their platforms common that they became indistinguishable, so people no longer bought the more expensive versions, viewing them as lacking sufficient performance differentiation to be worth the extra cost.

Army Interim and Objective Force planning efforts have also been exploring the use of spare "ready to fight" systems (RTFs) to replace broken or damaged weapon systems.[9] However, whether they would affect pulse A_o, pulse self-sufficiency, and maneuver force maintenance footprint depends primarily upon whether they would travel with the maneuver force or could be supplied during a combat pulse. And their value versus other resources (i.e., spare parts and maintainers) must be carefully analyzed for the relative benefits and

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[9] A float is an additional or "spare" end item owned by an organization above and beyond the organizational structure requirement that can be used to replace a temporarily unavailable end item (or a permanently unavailable end item, which will require replacement of the float). Traditionally, brigades have small numbers of floats to replace end items that are expected to be down for an inordinate length of time. In contrast, ready to fight systems are viewed as another maintenance or readiness resource to be used when logistics resources become stretched during periods of high operating tempo.

costs. Additionally, RTFs could affect refit period length and refit effectiveness (and thus, indirectly, pulse A_o) assumptions.

A REVIEW OF ARMY ORDs

In a review of recent Army ORDs, we found that almost every requirement discussed in the previous section has been used for at least one weapon system program, but rarely do programs use a wide cross-section of them (see Appendix E for a list of ORDs reviewed). Instead, a couple are used in one program, another couple in another, and so forth, resulting in inconsistent use of these metrics. It appears that different groups in the Army have thought about the different parts of this list, but the Army as a whole has not constructed a comprehensive standard set of equipment sustainment metrics that could serve as a reference guide.

We now review the degree to which each of the metrics has been used to define program requirements. Table 3.3 provides a comparison of recommended requirements and metrics with those that have been used. Reliability and maintainability requirements have received the most attention among the categories we have discussed. Typically, some form of MTBCF appears in ORDs, although a variety of definitions and metrics are used.[10] The other common metrics used to define requirements are MTTR and the MR, which combines MMH per maintenance action and MTBM. Since it combines reliability and elements of maintainability, the MR represents a higher-level goal that translates to the number of maintainers required given the MMH per maintenance action and the OMS/MP. Thus it is a driver of footprint and cost. It is also fairly common for ORDs for replacement-type systems (those that are a direct replacement for another system in terms of function rather those that introduce fun-

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[10] TRADOC has recently set mean time between system aborts (MTBSA) and mean time between essential function failure (MTBEFF) as standards. However, it has been suggested that other metrics continue to appear, because the starting point for an ORD is often the ORD for a similar, previously developed system. A system abort is a failure that prevents a system from being able to accomplish designated missions. Essential function failures are failures that degrade capability but do not prevent mission accomplishment or failures related to essential functions that do not impede operation in and of themselves. Combined with other EFFs, such failures could lead to system aborts. Examples include secondary sights and redundant circuit cards.

Table 3.3

A Comparison of Recommendations to Army ORDs

Requirement Category	Historical Use of Metrics for Equipment Sustainment Requirements	Potential Standard Metrics for Defining Sustainment Requirements
Availability	• Rare use of A_o • Rare use of “sortie” reliability (e.g., missile in-flight reliability)	• Pulse A_o (operational availability) — Use derived pulse A_i in some cases • Prob(successful sortie completion) • Specify pulse, refit, and sortie parameters[a]
Self-sufficiency	• Rare use of maintenance and spares self-sufficiency for a designated time period (e.g., 30 days) for a designated unit size	• Self-sufficiency pulse length
Equipment sustainment footprint	• Maintenance ratio and use of existing MOS, personnel, and equipment less/equal to current • Rare use of total deployment footprint	• Maintainers by echelon (cost and footprint driver); may be relative or maintenance ratio by echelon • Maintenance equipment lift requirements
Life cycle equipment sustainment cost	• SAR includes O&S costs • Use of O&S less/equal to current	• Total life cycle cost to “maintain” • Annual operation (cost per operating hour/mile) • Planned recapitalization • Spare parts provisioning • Investment in reliability (e.g., materiel)

Table 3.3—continued

Requirement Category	Historical Use of Metrics for Equipment Sustainment Requirements	Potential Standard Metrics for Defining Sustainment Requirements
Reliability	• Some form of MTBCF • Rare use of MTBM and MTBSM	• Standard form of MTBCF • MTBUM and MTBSM (by echelon)
Maintainability	• Recent use of FFP (very limited), FFD with FIR, FAR (very limited) • MTTR (sometimes by echelon) • MR (sometimes by echelon) • Rare use of MMH/SM • Miscellaneous features (e.g., org replaceable power pack) and rare use of percent UM-org level	• FFSP = Fn(FFP, FIR, FAR/NEOF Rate) • FFSD = Fn(FFD, FIR, FAR/NEOF Rate) • MTTR (by echelon) • MMH/UM (by echelon) • MMH/SM (by echelon) • Percent UM-crew, org, DS, GS
Fleet life cycle management	• Rare use (e.g., barrel life) • Plug in/plug out LRUs	• Specify replacement/recap/retirement schedule • Use estimate of reliability degradation in requirements analysis[a]
Supply support	• Rare use of fill rate requirements • Rare use of ALDT	• Local fill rate • Battle damage parts kit • Wholesale backorder rate • Percent of parts that are unique • Number and positioning of end item floats • Specify ALDT assumption[a]

[a] Critical assumptions that are necessary to determine the associated requirements.

damentally new capabilities or technologies) to specify that a system require the same number and type of personnel and equipment for support as those of the system it replaced.

A positive trend is that recent, major programs are making much greater use of diagnostic-oriented maintainability requirements, often using FFD and FIR metrics to define requirements. One ORD examined also used FFP and FAR. Many other ORDs recognize the need to use automated diagnostics that provide potential prognostic capability going forward, but until recently most just specified that the weapon system has to have built-in test/built-in test equipment (BIT/BITE) capability without quantifying the desired benefit.

In light of proposed Objective Force concepts that call for unit self-sufficiency during combat pulses, it is interesting to note that the requirements for one system currently in development include self-sufficiency without parts delivery or external maintenance support for a defined period. This was used in conjunction with a requirement for a specified level of local spare parts fill rate performance. Also of note is that one program specified a requirement for the percentage of maintenance actions that are within the capabilities of organizational-level maintenance, which is another type of requirement that may be of increasing interest as the Army strives to reduce maneuver force maintenance footprint.

While life cycle operating costs and other costs associated with life cycle support, such as for recapitalization, have traditionally not been stated as ORD requirements, they have been de facto requirements as a result of their inclusion in the Selected Acquisition Report (SAR). The SAR includes each major cost category.

Two major gaps consistently appear. The first is the lack of A_o usage or any other similar high-level metric directly related to warfighter mission needs. The absence of A_o, though, seems to be driven more by concerns with using it well, rather than whether it should be used at all. The second gap is the failure to explicitly treat changing maintenance demands over the course of a system's life. Such demands could be reflected in systematic degradation in pulse A_o and in increases in operating costs as reliability degrades as well as in preplanned recapitalizations to enable systems to meet operational and resource consumption goals over the full course of their service lives.

While pulse A_o is typically not used, the concept is often embedded in the requirements development process. To determine reliability and maintainability requirements, combat developments engineers must start from some higher-level goal. Often they target an average A_o over the time period and set of tasks specified in the OMS/MP. This is really an operational pulse, with the pulse length defined by the OMS/MP; thus the goal is pulse A_o. At other times the goal may be to keep a minimum number of systems, say four of six, available at all times over the series of tasks in the OMS/MP. This is akin to maintaining a minimum pulse A_o.

It seems that three factors then tend to combine to prevent carrying through the average or minimum pulse A_o target from reliability and maintainability requirements determination to inclusion as a program requirement. To derive reliability and maintainability requirements from an A_o target, ALDT (including spare parts) assumptions are necessary. The first factor has been a lack of good, supportable data to develop justifiable assumptions. The second is the inability to conduct a complete A_o test, which would have to include representative supply chain support. The third seems to be a hesitation to levy program requirements on internal DoD organizations.

To make the use of A_o viable, either A_o would have to be tested or it would have to be modeled using good assumptions. Additionally, it would probably require the use of some functional requirements that would be the responsibility of internal DoD organizations. While potentially difficult, these hurdles can be overcome. The next chapter includes a discussion of the pulse A_o evaluation problem.

Traditionally, requirements have been developed to serve as the basis of contractual specification for systems developers. They have been externally focused. However, requirements could also be used internally. Instead of being the basis for contractual specifications, they could form the basis of performance agreements accepted by organizational commanders. The resources to meet these performance agreements would be a necessary condition for the achievement of the performance targets. This would have the added benefit of helping to make support funding, such as for initial spare parts provisioning, and associated performance shortfalls more visible. In fact, the DoD as a whole is moving in directions that support this type of approach. The services are in the process of implementing performance-based logistics, which will consist of performance agreements between program managers and providers and their customers.[11] And the Defense Logistics Agency is planning to create performance agreements with its customers as it implements its Business Systems Modernization.

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[11] E.C. Aldridge, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, “Memorandum. Performance Based Logistics,” February 13, 2002.