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ASSESSING THE ABCT EQUIPMENT MODERNIZATION PROCESS WITH A SPREADSHEET MODEL OF A FINITE POPULATION, MULTI-SERVER MACHINE INTERFERENCE PROBLEM

December 2018

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ABSTRACT

This MBA project report focuses on the development of a spreadsheet model of a finite population queue to replicate the Armored Brigade Combat Team (ABCT) equipment modernization process. The purpose of this report is to assess the sensitivity of several key determinants of equipment modernization cycle time for policy recommendations. This analysis utilized a published spreadsheet formulation of a finite population, multi-server machine interference problem as the basis for the design of the spreadsheet model that supports the findings of this report. Key modifications to the model include the implementation of customer balking and reneging in the queueing system.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABCT	armored brigade combat team
ACR	armored cavalry regiment
AD	armored division
BCT	brigade combat team
BDE	brigade
BN	battalion
CAB	combined arms battalion
CAV	cavalry squadron
CD	cavalry division
FIFO	first-in, first-out service discipline
FT	fort
IBCT	infantry brigade combat team
ID	infantry division
IN	infantry
LIFO	last-1n, first-out service discipline
SIPB	service in priority basis
SIRO	service in random order
SQDN	squadron

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I. INTRODUCTION

A. BACKGROUND

The nature of armed conflict has changed in a way that is incomprehensible to the presumption of U.S. military preeminence. In this respect, the nation's strategic documents and corresponding doctrinal operating concepts recognize this as a paradigm shift (Department of Defense, 2018; U.S. Army Training and Doctrine Command, 2014). These documents conceptualize the state of modern warfare under the auspices of uncertainty and complexity.

1. Strategic Overview

According to the *Summary of the 2018 National Defense Strategy*, uncertainty manifests to the extent that peer rivals, rogue regimes, and non-state actors seek to challenge the post-Cold War geopolitical order (Department of Defense, 2018). Likewise, the *U.S. Army Operating Concept* explains that complexity pervades the operational context in which these U.S. competitors could possibly influence a global reshuffling of hegemonic power (U.S. Army Training and Doctrine Command, 2014). The *U.S. Army Operating Concept* further states that adversarial competitors to the United States, such as China and Russia, have invested in a broad range of military modernization efforts in the last twenty years (U.S. Army Training and Doctrine Command, 2014).

The *Army Operating Concept* concludes that the development and integration of new warfighting capabilities across multiple domains will challenge the long-standing warfighting overmatch[1] U.S. forces once enjoyed (U.S. Army Training and Doctrine Command, 2014). The implications for U.S. forces, particularly those employed by the U.S. Army, are profound.

[1] Overmatch is tantamount to obtaining an overwhelming advantage that is difficult for an adversary to counter.

2. U.S. Army Disposition

Senior leaders of the U.S. Army acknowledge that the Department of the Army must keep pace in the race with strategic competitors to develop warfighting capabilities (Murphy & Milley, 2016; U.S. Army Training and Doctrine Command, 2015). The U.S. *Army Operating Concept* states that the U.S. Army must prioritize the resources it apportions for modernization efforts for the mitigation of the immediate operational risk posed by emerging threats (U.S. Army Training and Doctrine Command, 2014).

Consequently, senior leaders of the U.S. Army acknowledge that the long-term investment in the ground maneuver platforms of tomorrow is not an immediate priority (Murphy & Milley, 2016). The Army's near-term objective, according to both the Secretary and Chief of Staff of the Army, is to pursue a regime of incremental modernization needed to extend the service-life of the previous generation of equipment currently on-hand (Murphy & Milley, 2016). This is particularly true for the U.S. Army's Armored Brigade Combat Teams (ABCT) and their array of M1 Abrams tanks, M2 Bradley fighting vehicles, and M109 Paladin self-propelled artillery.

B. RESEARCH OBJECTIVES

The intent of this report is to determine the relative influence of several key variables on the ABCT equipment modernization process. These variables include the number of operational commitments, readiness level, the number of materiel fielding teams, and the time intervals germane to both ABCT availability and the completion of individual modernization activities. Building a model to account for these variables is key to identifying the drivers of modernization cycle time. Conceptualizing the ABCT equipment modernization process as a queueing system was necessary for the creation of the model. At a granular level, this report interprets the process as a finite-population, multi-server machine interference problem.

C. SCOPE

This report focuses exclusively on the U.S. Army's inventory of Active Component ABCTs. It does so independently of Reserve Component ABCTs and prepositioned stocks of ABCT equipment.

D. METHODOLOGY

This report is the culmination of a research effort that included the comprehensive review of queueing theory, the compilation of open source deployment and equipping data, and the development and simulation of a model to replicate the equipment modernization process.

E. ORGANIZATION OF THE REPORT

Five additional chapters beyond this introduction comprise the remainder of this report. Chapter II: Literature Review investigates queueing theory as the basis for interpreting the ABCT equipment modernization process. Chapter III: Data Consolidation reviews the deployment and equipping data instrumental to the functionality of the report's model. Chapter IV: Model Formulation illustrates the logical argumentation used for this report's modeling replication of a queuing system. Chapter V: Simulation and Analysis details the statistical analysis of simulated model outputs. Chapter VI: Recommendations and Conclusions operationalizes the statistical analysis into policy recommendations as well as recommendations for future research.

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II. LITERATURE REVIEW

A. INTRODUCTION

This report will utilize a spreadsheet model of a finite population machine interference problem to conduct an analysis of the ABCT modernization process. This chapter will introduce the basic concepts queueing theory to frame further discussion of the machine-interference problem.

B. QUEUEING THEORY

The review of standard texts and research publications pertinent to queuing theory revealed a broad body of knowledge oriented on what is fundamentally the analytical interpretation of waiting lines (Edwards & Chelst, 2002; Giachetti, 2013; Hillier & Lieberman, 1995; Ibe, 2011; Yadav & Malik, 2014). A range of articles in scholarly journals conclude that waiting lines occur whenever the interaction between customers and servers is not synchronized (Jain, Mohanty, & Böhm, 2016; Subba Rao, Gunasekaran, Goyal, & Martikainen, 1998). One article describes that a queue forms in this process whenever a resource is unable to begin service for a customer (Edwards & Chelst, 2002).

C. PRACTICAL APPLICATIONS

Queue waiting times cause process inefficiencies that imperil the profit as well as the quality of work performed by a server. One journal article published by *IEEE Potentials* describes queuing theory as an area of research that originated with A. K. Erlang's investigation of telephone switches in the early 1900's (Tad, 1996). Other journal articles note that the application of queueing theory over the last century has reverberated across a broad spectrum of industries in pursuit of process improvement (Mandelbaum & Hlynka, 2008; Subba Rao, et al., 1998; Tadj, 1996).

For instance, in the manufacturing and production space, scholars and manufacturers have used queuing theory to better understand resource allocation and the occurrence of bottlenecks in production lines (Subba Rao, et al., 1998). Moreover, in the transportation and logistics fields, the utility of queueing models has optimized the reduction of flight delays at airports (Jacquillat, Odoni, & Webster, 2017) and has determined the optimal ship throughput for profitable harbor operations (Edmond & Maggs, 1978).

Of course, military applications of queueing theory have explored everything from production consolidation efforts for jet engines (Krentz, 1991) to the efficiency of amphibious operations (Hey, 1986; Peters, 1994). This small sampling is far from comprehensive, but nevertheless alludes to the usefulness of queuing theory in the understanding of operational processes.

D. QUEUING PROCESS

An explanation of queuing theory fundamentals follows.

1. Overview

The rudimentary construct of most queueing systems, either man-made or naturally occurring, is typically a multi-stage sequence. As described in several publications, this sequence originates with a customer's arrival to the system (Cooper, 2010; Giachetti, 2013; Jain, et al., 2016). These publications also describe that upon arrival, a customer then enters a queue before receiving some type of service and ultimately departing the system (Cooper, 2010; Giachetti, 2013; Jain, et al., 2016).

2. Customer Arrival

According to one introductory operations research publication, queueing systems necessitate the arrival of customers from a calling population of either finite or infinite size (Hillier & Lieberman, 1995). Another introductory operations research publication notes that customers typically arrive to queuing systems in a random pattern that follows a Poisson distribution (Yadav & Malik, 2014).

E. WAITING LINES

The next stage of a queueing system entails the formation and management of waiting in lines for customers in the instance when service is not readily available. As explained in the *Handbook of Industrial and Systems Engineering*, queues have either a finite or infinite capacity (Giachetti, 2013). If the rate that customers arrive to the queue is greater than the service rate of the system, then a queue of some length will form. The inference is that a queue will continue to grow until either the queue reaches its maximum capacity, or until a server eventually selects a sufficient number of customers for service.

1. Service and Departure

Determining the priority of how and when customers waiting in a queue receive service is a matter of the type of queue discipline the system employs. Though there exists a variety of queue disciplines, two operations research publications declare the first-come-first-served (FIFO) as the most common (Hillier & Lieberman, 1995; Tadj, 1996).

Upon selection from a queue, a customer receives service in the next stage of the system. As described in *Operations Research*, customer service occurs in at least one service facility, within which customers receive service from at least one server (Yadav & Malik, 2014). Furthermore, as described by Yadav & Malik, customers engage servers arrayed in a parallel service channel (2014). *Introduction to Operations Research* expounds by noting that customer throughput in queueing systems with multiple service facilities occurs in sequential stages (Hillier & Lieberman, 1995). Hillier & Lieberman conclude that customers will continue to encounter servers arrayed in parallel service channels, but will progress from one facility to the next along a serial service channel (1995).

F. THE MACHINE INTERFERENCE PROBLEM

As previously alluded, the study of queues has a broad range of applications. Therefore, it follows that there is also some level of differentiation that exists between the analytical queuing models used for these various applications. The process by which the U.S. Army modernizes its ABCTs fits one particular type of queuing model known by researchers as the machine interference problem. The following section will discuss the machine interference problem in further detail.

1. Concept

Two surveys of the research pertaining to the machine interference problem catalog in great detail the variety of approaches used to decompose and assess this particular type of queueing situation (Haque & Armstrong, 2007; Stecke & Aronson, 1985). Scholarly articles assert that machine interference queueing systems involve some number of identical machines that perform work, while a smaller number of identical repair technicians fix the machines whenever they break (Eben-Chaime, 1998; Jayaraman & Matis, 2010). The interference or waiting time caused to any machine's availability to perform work is a consequence of several factors. Researchers attribute interference to the random rates at which the machines break down as well as the repair technician's capacity to return the machines to operation in a timely fashion (Seal, 1995; Stecke & Aronson, 1985).

From a management perspective, the end state for analyzing this type of problem is to optimize queue performance measures to keep as many machines operating as possible. According to several research publications, the performance measures specific to machine interference problems include machine breakdown rates (interarrival times), arrival patterns to the waiting queue, the number of available repairmen (server size), and the time it takes a server to render a repair (service rate) (Haque & Armstrong, 2007; Jayaraman & Matis, 2010).

2. Customer Population

In the context of ABCT modernization, the population of ABCTs is analogous to the population of machines in a generic machine interference problem. One caveat according to the Congressional Budget Office, is that the U.S. Army currently has only ten active-component ABCTs in the calling population (Congressional Budget Office, 2016). In queueing terminology, this population is finite and relatively small.

Further complicating matters are the constraints of the modernization process that govern how the U.S. Army calls for an ABCT to receive an upgrade (machine repair). A general assumption of this report is that no single ABCT will receive a second upgrade before all other ABCTs have received their first upgrade. Said differently, the U.S. Army must apply one increment of an equipment upgrade to all ten ABCTs before any one of the ABCTs are eligible to receive the second increment. This constraint causes the calling population of ABCTs to reduce by one each time one ABCT receives an upgrade. All ten ABCTs rejoin the calling population after the final ABCT receives its upgrade.

3. Customer Arrival

In the classic machine interference problem, machine arrivals to the repair queue are the result of random mechanical malfunctions. In the case of ABCT modernization, this arrival rate is a representation of the U.S. Army's decision to designate an ABCT to enter the modernization queue. An ABCT will refuse to join the modernization process if the queue has reached its Army mandated capacity. An ABCT may also leave the queue prematurely before receiving service. Research publications about queueing theory describe these aforementioned queue behaviors respectively as balking and reneging (Haque & Armstrong, 2007; Jayaraman & I. Matis, 2010).

4. Service and Departure

Repair technicians are the typical servers in a machine repair problem. In the instance of ABCT modernization, materiel fielding teams or materiel fabrication teams from defense contractor program management offices fill the role of servers in a queue. As with any multi-server queue, these servers operate in parallel.

G. SPREADSHEET MODELING OF A QUEUE

Some academic arguments from the operations research and management science academic disciplines deride the use of spreadsheet models (Gass, et al., 2000). However, other arguments contend that spreadsheet models retain near universal utility in demystifying problems of significant analytic complexity (Grossman, 1999; Gupta & Karaesmen, 1994). Such problems include the finite population queue, queues with balking and reneging, and multi-server queues. The subject of this report, the ABCT modernization process, combines all of these queue variations as noted in this report's discussion of the machine interference problem. Spreadsheet modeling may provide a more intuitive way to assess the U.S. Army's equipment modernization process.

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III. DATA CONSOLIDATION

A. INTRODUCTION

This chapter will discuss the data utilized to create the probability distributions necessary for the formulation of this report's spreadsheet model. The model utilizes two separate probability distributions to randomly allocate intervals of time to ABCTs. One interval of time pertains to an ABCT's window of availability to partake in equipment modernization activities. The other interval of time pertains to the amount of time it takes for a materiel fielding team to render services. The model collectively utilizes these two intervals of time as the determinants of ABCT balking and reneging from the ABCT equipment modernization process.

B. ABCT AVAILABILITY

ABCT windows of availability are a function of ABCT dwell time between operational deployments. In the interest of simplicity, this report assumes that a window of availability consumes only one-third of an ABCT's dwell time. To create the cumulative probability distribution for ABCT windows of availability, this report first deduced ABCT dwell time from ABCT deployment and redeployment dates that have occurred since 2003. Each occurrence of dwell time constituted an occurrence of a derivative window of availability. The report then executed a histogram tabulation of all computed windows of availability. This tabulation ultimately drove the creation of the cumulative probability distribution for windows of availability.

This cumulative probability distribution is the indirect product of an extensive research effort. This research surveyed open-source media and publications to confirm ABCT deployment and redeployment dates. These media and publications included national, local, and installation-specific news outlets, official military press releases and unit histories, as well as defense studies and other national security related works.

The U.S. Army's inventory of ABCTs have activated, in-activated, relocated, and have changed configuration multiple times since 2003. Additionally, the total inventory of active component ABCTs has shrunk from 18 to 10 brigades-sized armored formations over the same time span. As a result of this ABCT force management activity, this report's tabulation of ABCT dwell time only accounts for ABCTs that conducted more than one deployment as an armored brigade. Table 1 defines the probability distribution used by the model. Table 1 consolidates the information derived from this research while Table 2 defines the resultant probability distribution used by the model.

Table 1. ABCT Availability (Months) for Modernization between Operational Requirements: 2003–2018

ABCT	Interval 1	Interval 2	Interval 3	Interval 4	Interval 5	Interval 6	Interval 7
3ACR(FT Carson, CO) to 3ACR(FT Hood, TX)	3	7	6				
1/1CD(FT Hood, TX)	6	4	6	9	5	6	
2/1CD(FT Hood, TX)	7	3	5	6	5	5	
3/1CD(FT Hood, TX)	6	4	5	21			
4/4ID(FT Hood, TX) to 4/1CD(FT Hood, TX)	6	5	5				
1/1AD(Germany)	6						
2/1AD(Germany) to 2/1AD(FT Bliss, TX)	5	5	4				
4/1CD(FT Bliss, TX) to 4/1AD(FT Bliss, TX) to 3/1AD(FT Bliss, TX)	5	6	2	12			
2/1ID(Germany) to 172nd IN BDE(Germany)	5	4					
1/1ID(FT Riley, KS)	5	19	11	6			
3/1AD(Germany) to 2/1ID(FT Riley, KS)	3	11	5	16	4		
2/2ID(Korea) to 2/2ID (FT Carson, CO)	5						
1/3ID(FT Stewart, GA)	5	4	7	17	1	1	5
2/3ID(FT Stewart, GA)	5	5	6				
3/3ID(FT Benning, GA)	6	5	5	7			
1/4ID(FT Hood, TX) to 1/4ID(FT Carson, CO)	7	5	4	7			
2/4ID(FT Carson, CO)	7	7	7	6			
3/4ID(FT Carson, CO)	6	4	5	16	4		

Adapted from Banzhaf (2014); Beardsley (2012); Boyce (2008); Boyd (2017); Burge (2015); Coleman (2017); Department of the Army (2011, 2014); Dickstein (2016); Dougherty (2006); First Cavalry Association (n.d.a, n.d.b, n.d.c); Global Security (n.d.a, n.d.b),Graham (2009); Graham-Ashley (2011); Ingram (2013); Johnson (2012); Johnson (2009); Johnson (2013); KKTV News (2004); Knowles (2015); Larsen (2012); Miles (2008); Morgan (2011); Oliver (2010); Porch (2012, 2013); Poulin (2011); Robles (2015); Robson (2006); Rogers (2012); Scott (2013); Senger (2011); Tan (2015); U.S. Army, 2nd Infantry Division (n.d.); U.S. Army, Fort Hood (2015); U.S. Army, Fort Riley (2014, n.d.).

Table 2. Windows of Availability Cumulative Probability Distribution

Months Available	Frequency	Probability	Lower Limit	Upper Limit
1	2	0.029	0.000	0.029
2	1	0.014	0.029	0.043
3	3	0.043	0.043	0.087
4	9	0.130	0.087	0.217
5	22	0.319	0.217	0.536
6	14	0.203	0.536	0.739
7	9	0.130	0.739	0.870
8	0	0.000	0.870	0.870
9	1	0.014	0.870	0.884
10	0	0.000	0.884	0.884
11	2	0.029	0.884	0.913
12	1	0.014	0.913	0.928
13	0	0.000	0.928	0.928
14	0	0.000	0.928	0.928
15	0	0.000	0.928	0.928
16	2	0.029	0.928	0.957
17	1	0.014	0.957	0.971
18	0	0.000	0.971	0.971
19	1	0.014	0.971	0.986
20	0	0.000	0.986	0.986
21	1	0.014	0.986	1.000
Observations	69			

C. MATERIEL FIELDING TEAM SERVICE TIME

The complexity and volume of work necessary to field modernized equipment to ABCTs or to physically modify old ABCT equipment causes variations to service time. To develop the probability distribution of this variance in service time, this report utilizes data compiled from briefings by the force management division of the U.S. Army's Third Corps (III Corps) headquarters, Fort Hood, Texas. These unclassified PowerPoint presentations are accessible via common access card upon approved system access request via III Corps online web portal.

III Corps is the parent headquarters for the U.S. Army's 1st Cavalry Division (Fort Hood, Texas), 1st Armored Division (Fort Bliss, Texas), 1st Infantry Division (Fort Riley, Kansas), and the 4th Infantry Division (Fort Carson, CO) among other supporting units. Collectively, eight of the Army's ten active component ABCTs are subordinate to the division headquarters that fall under the command of III Corps. The observed data in Table 3 reflects the expected service time interval for each ABCT equipment modernization effort that occurred within III Corps between 2016 and 2018. Table 4 defines the cumulative probability distribution for fielding team service time.

Table 3. Materiel Fielding Team Service Time (Months): 2016 - 2018

ABCT Parent Headquarters	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9
1CD(Fort Hood, TX)	4	3	3	2	1	6	6	4	3
1AD(Fort Bliss, TX)	6	4	2	7	2	6			
1ID(Fort Riley, KS)	4	7	5	3	4	4	2	5	
4ID(Fort Carson, CO)	9	3	4						

Adapted from III Corps Force Management Division (2017a, 2017b, 2017c, 2017d).

Table 4. Cumulative Probability Distribution for Fielding Team Service Time

Months	Frequency	Probability	Lower Bound	Upper Bound
1	1	0.038	0.000	0.038
2	4	0.154	0.038	0.192
3	5	0.192	0.192	0.385
4	7	0.269	0.385	0.654
5	2	0.077	0.654	0.731
6	4	0.154	0.731	0.885
7	2	0.077	0.885	0.962
8	0	0.000	0.962	0.962
9	1	0.038	0.962	1.000
Observations:	26			

IV. MODEL FORMULATION

A. INTRODUCTION

This chapter describes the analytical formulation of the model. The model conceptualizes the ABCT equipment modernization process as a finite-population, multi-server machine interference problem. It does so by utilizing the framework of a spreadsheet model published in the *International Journal of Operations and Production Management* (Seal, 1995). Key revisions to Seal's model include the formulation of customer balking and reneging from the queueing system.

B. FOUNDATIONAL BASIS

Chapter 2 discusses the general concept of the machine interference problem in great detail. As depicted in Figure 1, a machine interference problem is a closed system that includes a population of machines, a queue, and technicians that render repair services whenever machines break down.

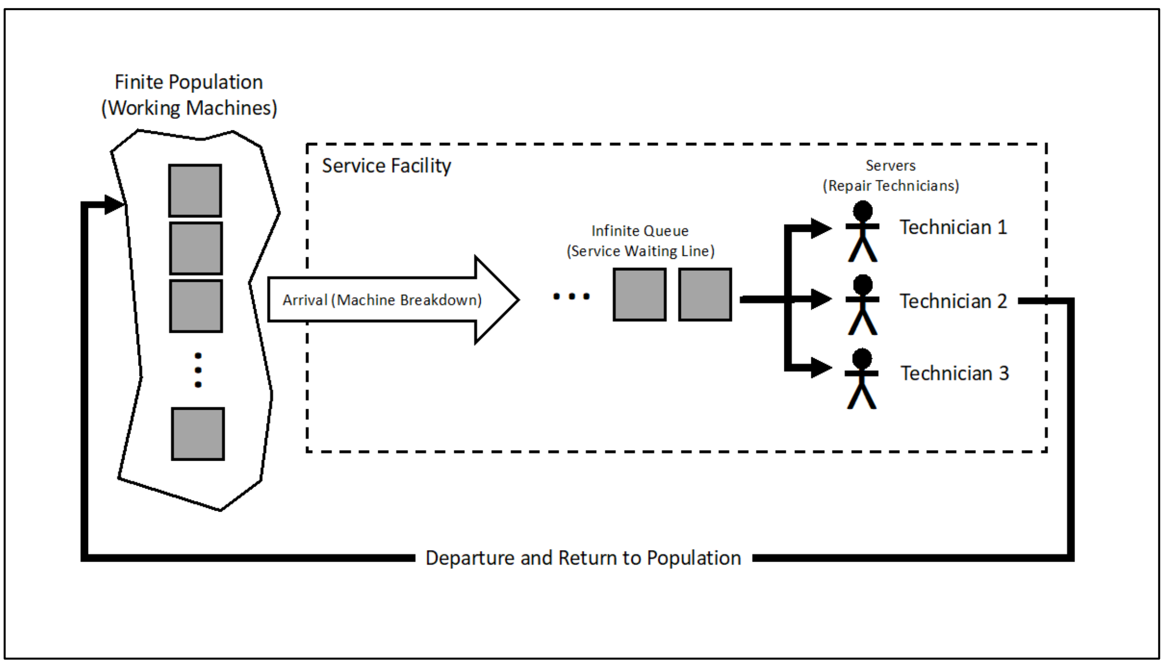

Figure 1. Machine Repair Process. Adapted from Ibe (2011).

In the specific case of ABCT modernization, a finite number of ABCTs is analogous to a population of machines. Much like in a standard machine interference problem, ABCT arrival to the queuing system from the calling population is random. However, whereas generic machines randomly breakdown and require repair, the U.S. Army randomly selects ABCTs to receive an equipment upgrade. ABCTs, much like generic machines, wait in a queue to receive service. However, due to operational demand, ABCTs cannot wait indefinitely in the service queue. Consequently, ABCTs may balk or renege from the modernization process prematurely under certain conditions. Figure 2 illustrates this process.

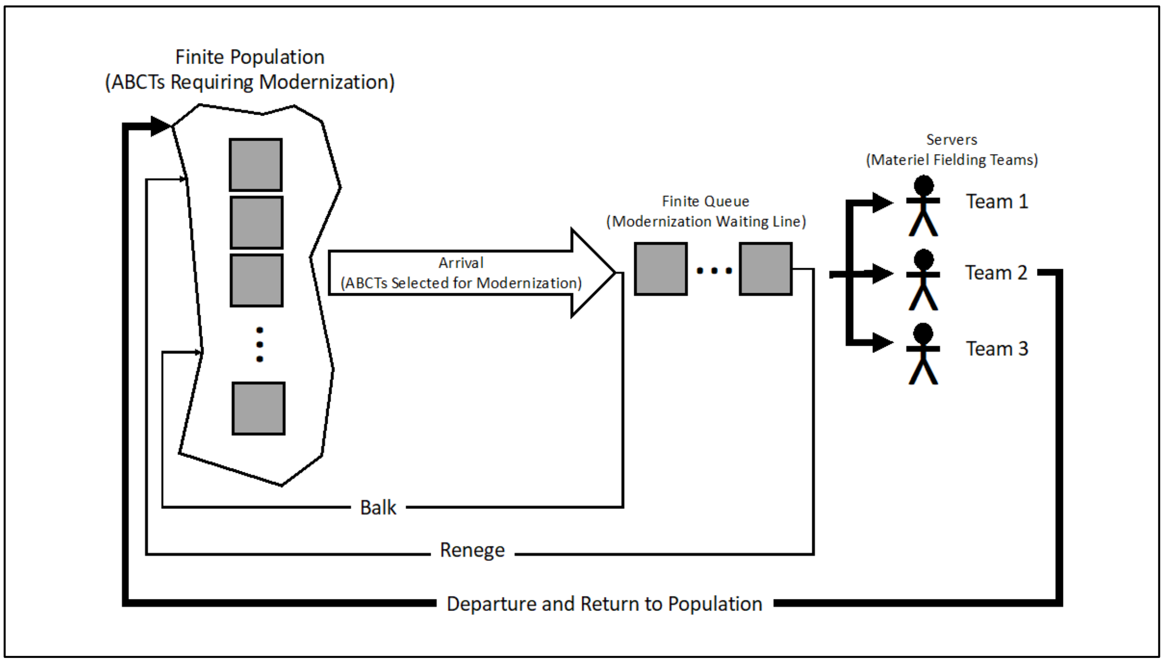

Figure 2. ABCT Modernization Process. Adapted from Ibe (2011).

Unlike generic machine interference problems with unlimited queue capacity, the U.S. Army explicitly limits the number of ABCTs it can have in the modernization queue at any one time. Operational demand and readiness directives preclude the unconstrained allocation of ABCTs to non-mission essential tasks such as equipment modernization. When the U.S. Army does select ABCTs to enter the modernization process, materiel fielding teams function in the same way as machine repair technicians.

This model replicates a service in random order (SIRO) service discipline in lieu of either a first-in/first-out (FIFO), last-in/first out (LIFO), or other service discipline. Mission requirements, ABCT force structure, and budget constraints exist in a malleable state that could render structured service disciplines as infeasible in practice.

Upon selecting an ABCT for upgrade, materiel fielding teams will complete modernization activities in randomly determined intervals of time dictated by a probability distribution. Unlike generic machines that immediately return to the calling population upon repair, a newly modernized ABCT will not. ABCTs return to the calling population only when all other ABCTs have received the same upgrade. In other words, the U.S. Army designates its ABCTs to receive new upgrades, not the same upgrade multiple times. This model assumes that the Army fields one instead of multiple increments of equipment modernization at a time.

C. DEFINING THE PROCESS

The model developed for this report replicates a complex, multi-stage process as illustrated by the flowchart in Figure 3.

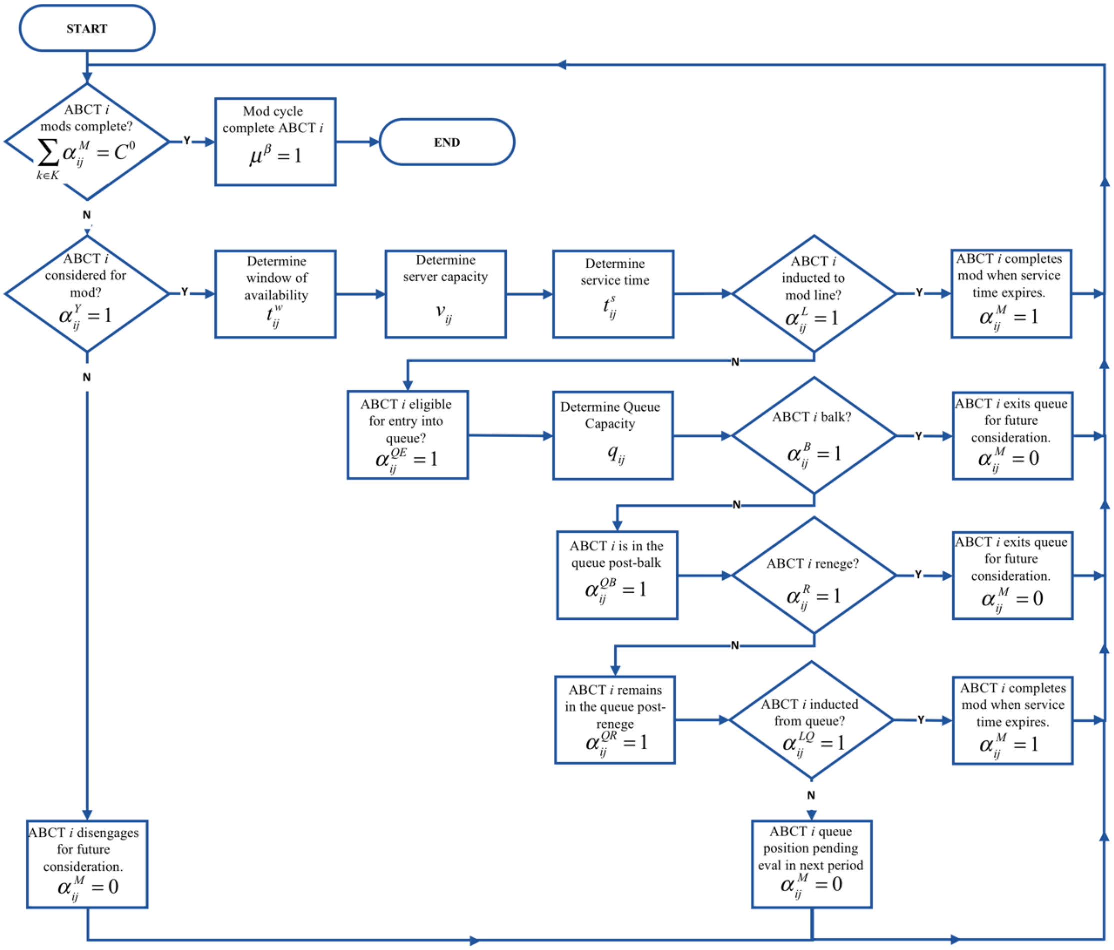

Figure 3. Flowchart for the ABCT Equipment Modernization Process

To facilitate further discussion of this overarching process and the correlated sub-processes within the spreadsheet model, the following definitions apply.

1. Indices and Index Sets

D Set of enduring ABCT commitments to deploy; $\{d \mid d \in \mathbb{Z}^{+}\}$

I Set of ABCTs; $\{ABCT1, ABCT2...\}, i \in I$

J Set of periods (months); $\{j \mid j \in \mathbb{Z}^{+}\}$

K Set of ABCTs i in period j; $\{k \mid k \in \mathbb{Z}^{+}\}$

R Set of readiness levels (percentage); $\{r \mid r \in \mathbb{R}; 0 < r < 1\}$

T Set of units of time (months); $\{t \mid t \in \mathbb{Z}^{+}\}$

V Set of Materiel Fielding Teams; $\{v \mid v \in \mathbb{Z}^{+}\}$

X Set of random variables; $\{x \mid x \in \mathbb{R}; 0 < x < 1\}$

A^{B} Set of ABCT balk decisions; $\{0,1\}, \alpha^{B} \in \mathrm{A}^{B}$

A^{L} Set of ABCT induction decisions; $\{0,1\}, \alpha^{L} \in \mathrm{A}^{L}$

A^{LQ} Set of ABCTs queue induction decisions; $\{0,1\}, \alpha^{LQ} \in \mathrm{A}^{LQ}$

A^{M} Set of ABCT modernization decisions; $\{0,1\}, \alpha^{M} \in \mathrm{A}^{M}$

A^{Q} Set number of ABCTs in the queue; $\{\alpha^{Q} \mid \alpha^{Q} \in \mathbb{Z}^{+}\}$

A^{QB} Set of ABCT post-balk queue position decisions; $\{0,1\}, \alpha^{QB} \in \mathrm{A}^{QB}$

A^{QE} Set of ABCT queue eligibility decisions; $\{0,1\}, \alpha^{QE} \in \mathrm{A}^{QE}$

A^{QR} Set of ABCT post renege queue position decisions; $\{0,1\}, \alpha^{QR} \in \mathrm{A}^{QR}$

A^{R} Set of ABCT renege decisions; $\{0,1\}, \alpha^{R} \in \mathrm{A}^{R}$

A^{Y} Set of ABCT consideration decisions; $\{0,1\}, \alpha^{Y} \in \mathrm{A}^{Y}$

H Set of periods j in modernization cycle η; $\{\eta \mid \eta \in \mathbb{Z}^{+}\}$

$\mathbf{M}$ Set of equipment modernization cycles; $\{\mu \mid \mu \in \mathbb{Z}^{+}\}$

$\mathbf{M}^{\beta}$ Set of modernization cycle completion decisions; $\{0,1\}, \mu^{\beta} \in \mathbf{M}^{\beta}$

$\mathbf{M}^{\phi}$ Set of completed modernization cycles; $\{\mu^{\phi} \mid \mu^{\phi} \in \mathbb{Z}^{+}\}$

$\mathbf{P}$ Set of cumulative elapsed cycle times; $\left\{\rho \mid \rho \in \mathbb{Z}^{+}\right\}$

2. Model Configuration Variables

C^0 Maximum number of ABCTs in the calling population of ABCTs

j^{max} Maximum number of periods observed in one trial

μ^{max} Maximum number of equipment modernization cycles observed in one trial

3. Independent Variables

d^0 Initial number of enduring commitments to deploy assessed throughout a scenario

q^0 Initial queue capacity

r^0 Readiness level assessed throughout a scenario

t^s Time interval for MFT service time

t^w Time interval for ABCT windows of availability

v^0 Initial Number of Materiel Fielding Teams assessed throughout a scenario

4. Stage-Dependent Variables

q_{ij} Queue capacity available for ABCT i in period j

t_{μ}^{c} Cycle time of modernization cycle μ

t_{ij}^{s} Time interval for MFT service time ABCT i in period j

t_{ij}^{w} Time interval for ABCT windows of availability ABCT i in period j

$t_{i\mu}^{\theta}$ Takt time between modernization activities for ABCT i

$\bar{t}_{i\mu}^{\theta}$ Average takt time for all ABCTs in modernization cycle μ

t^{ψ} Average takt time for all ABCT i for all modernization cycles μ

t^{ζ} Average cycle time for all modernization cycles μ

v_{ij} Number of Materiel Fielding teams available for ABCT i in period j

α_{ij}^{B} Balk status of ABCT i in period j

α_{ij}^{L} Induction status of ABCT i in period j

α_{ij}^{LQ} Induction status (from queue) of ABCT i in period j

α_{ij}^{M} Modernization status of ABCT i in period j

α_{j-1}^{Q} The number of ABCTs in the modernization queue in the previous period j

α_{ij}^{QB} Post-balk queue status of ABCT i in period j

α_{ij}^{QE} Queue eligibility of ABCT i in period j

α_{ij}^{QR} Post renege queue status of ABCT i in period j

α_{ij}^{R} Renege status of ABCT i in period j

α_{ij}^{Y} Consideration for upgrade status of ABCT i in period j

$\delta^{s}(x)$ Probability distribution for deterministic service times ABCT i in period j

$\delta^{w}(x)$ Probability distribution for deterministic windows of availability ABCT i in period j

$\varepsilon(x)$ Probability distribution for ABCT consideration for modernization ABCT i in period j

μ^{β} Modernization cycle completion status

μ^{ϕ} Number of completed modernization cycles

$\rho_{\mu}^{\max}$ Aggregate equipment modernization time

ρ_{μ} Elapsed periods to completion for equipment modernization cycle μ

$\rho_{i\mu-1}^{\lambda}$ Period number at the end of the previous modernization cycle for ABCT i

$\rho_{i\mu}^{\pi}$ Period number at the beginning of the current modernization cycle for ABCT i

$\sigma^{s}(x)$ Probability distribution for deterministic service times ABCT i in period j

$\sigma^{w}(x)$ Probability distribution for stochastic windows of availability ABCT i in period j

τ_{ij}^{s} Time interval for remaining MFT service time ABCT i in period j

τ_{ij}^{w} Time interval for remaining ABCT windows of availability ABCT i in period j

D. MODEL FORMULATION.

This section will discuss the model's approximation of ABCT equipment modernization. The model's formulation entails calibration of a scenario, the equipment modernization model, and the calculation of forecasted dependent variables.

1. Scenario Calibration

The model induces stochastic behavior by the use of probability distributions. These distributions respectively pertain to: 1) the consideration of ABCTs for equipment modernization; 2) the allocation of ABCT windows of availability; and 3) fielding team service time. These probability distributions result from the calibration of the model's five independent variables. Each combination of variables constitutes an individual model scenario.

a. Determine the Probability of Consideration

The probability that the model considers an ABCT for equipment modernization p_{ij}^{Z} is the product of the probability that an ABCT is available for modernization p^{A} and the probability that an ABCT is eligible for equipment modernization p^{E}. Several steps must occur before the model calculates $p_{ij}^{Z} = p^{A} p^{E}$. The algorithm for determining the probability of consideration follows.

1. Select the independent variables from which the model derives p^{A} and p^{E}. Of particular interest are the initial calling population C^{0}, the readiness level r^{0}, and the number of enduring operational commitments d^{0}.

2. Determine system variables for the formulation of p^{A} and p^{E}. The model derives the number of ABCTs required to conduct enduring commitments and no-notice contingencies from the independent variable that specifies the readiness level r^{0}. The readiness level represents the portion of the Army's inventory of ABCTs that must remain combat-ready even if the ABCT is not deployed. This is inclusive of the number of ABCTs that already must meet known operational demand. Intuitively, the requirement cannot be less than the portion of the ABCT inventory that must forward deploy in support of enduring operational commitments. The expressions for this formulation follow.

$$r^{\kappa} = \begin{cases} \dfrac{d^0}{C^0}, & r^0 < \dfrac{d^0}{C^0} \\ \lceil r^0 \rceil, & r^0 \geq \dfrac{d}{C^0} \end{cases} \tag{1}$$

$$n = \lceil r^{\kappa} C^0 \rceil \tag{2}$$

$$g = C^0 - d^0 \tag{3}$$

$$h = C^0 - n \tag{4}$$

where

r^{κ} = adjusted readiness level

n = the number of ABCTs required to conduct both enduring operational commitments and no-notice contingency missions

g = the number of ABCTs not required to conduct enduring commitments

h = the number of ABCTs not required to conduct enduring commitments or contingency operations.

3. Calculate p^A and p^E. The probability of availability p^A and the probability of eligibility p^E differ in that the population of available ABCTs include the number of ABCTs not required to conduct a known rotational deployment. These known deployments constitute a fixed requirement that the Army must fulfill. On the other hand, this report classifies ABCT eligibility as the number of ABCTs that are neither required to support fixed operational requirements nor unknown requirements that require the Army to deploy an ABCT on short notice. Expressions for these probabilities follow.

$$p^A = \frac{g}{C^0} \tag{5}$$

$$p^{E} = \frac{h}{C^{0}} \tag{6}$$

where

C^{0} = the calling population of ABCTs,

p^{A} = the probability than an ABCT is available for equipment modernization,

p^{E} = the probability that an ABCT is eligible for equipment modernization.

4. Determine the probability that the model considers an ABCT for equipment modernization p_{ij}^{Z}. The model assigns a randomly generated variable to ABCTs it has yet to consider for equipment modernization. It then compares this random value to the probability of consideration p_{ij}^{Z}. It then determines whether an ABCT arrives from the calling population for service. The expression for this probability follows.

$$p_{ij}^{Z} = p^{A} p^{E} \tag{7}$$

where

p_{ij}^{Z} = the probability that an ABCT in a given period is considered for equipment modernization.

b. Defining Probability Distributions for Windows of Availability and Service Time

The model considers two separate and randomly generated intervals of time. One of these intervals, Windows of Availability t^{w}, accounts for the length of time that an ABCT may remain available to participate in modernization activities once the model considers it for entry into the system. The second time interval, Materiel Fielding Team

Service Time t^s, accounts for the length of time it takes a fielding team to complete an equipment upgrade.

A deterministic interval of time for t^w or t^s, as interpreted by the model, is one in which an initial time interval declared retains a constant value throughout a trial-run of the model. In other words, the model will allocate the same value for t^w or t^s for any ABCT designated to receive a window of availability or service time in any period. To the contrary, a stochastic declaration for t^w or t^s indicates that the model will randomly generate time intervals of various duration such that a data-driven distribution of values governs the frequency that the model assigns any particular interval of time. As such, the model may assign a different window of availability to each ABCT as it arrives to the equipment modernization process from the calling population.

The model's calibration of deterministic or stochastic time intervals occurs during the selection of the model's input variables. The following algorithm explains the procedure that model uses to calibrate the distributions it uses to determine the aforementioned intervals of time.

1. Determine if the model should evaluate ABCT windows of availability t^w as a deterministic time interval δ^w. If windows of availability are not deterministic, then the model evaluates a stochastic variable based on a cumulative probability distribution $\sigma^w(x)$. The expression of this determination follows.

$$t^w = \delta^w \tag{8}$$

or

$$t^w = \sigma^w(x) \tag{9}$$

where□

$$\sigma^w(x)=\begin{cases}1, & 0<x\le 0.029\\ 2, & 0.029<x\le 0.043\\ 3, & 0.043<x\le 0.087\\ 4, & 0.087<x\le 0.217\\ 5, & 0.217<x\le 0.536\\ 6, & 0.536<x\le 0.739\\ 7, & 0.739<x\le 0.870\\ 9, & 0.870<x\le 0.884\\ 11, & 0.884<x\le 0.913\\ 12, & 0.913<x\le 0.928\\ 16, & 0.928<x\le 0.957\\ 17, & 0.957<x\le 0.971\\ 19, & 0.971<x\le 0.986\\ 21, & 0.986<x<1\end{cases}.$$

2. Determine if the model should evaluate materiel fielding team service time t^s as a deterministic variable based on a probability distribution δ^s. If service time is not deterministic varialbe, then the model evaluates it as a stochastic variable based on a cumulative probability distribution $\sigma^s(x)$. The expression of this determination follows.

$$t^s=\delta^s \tag{10}$$

or

$$t^s=\sigma^s(x) \tag{11}$$

where

$$\sigma^s(x)=\begin{cases}1, & 0<x\le 0.038\\ 2, & 0.038<x\le 0.192\\ 3, & 0.192<x\le 0.385\\ 4, & 0.385<x\le 0.654\\ 5, & 0.654<x\le 0.731\\ 6, & 0.731<x\le 0.885\\ 7, & 0.885<x\le 0.962\\ 9, & 0.962<x<1\end{cases}.$$

E. ABCT EQUIPMENT MODERNIZATION PROCESS ALGORITHM

The model executes a multi-period replication of the equipment modernization process. The flowchart previously depicted in Figure 3 illustrates one period of this process. The overarching algorithm of the model follows.

1. Determine equipment modernization completion status
2. Determine an ABCT's status regarding its consideration for modernization
3. Determine an ABCT's window of availability if it is under consideration for modernization
4. Determine Materiel Fielding Team availability to provide service
5. Determine Materiel Fielding Team service time
6. Determine if an ABCT qualifies for induction into an equipment modernization line
7. Determine if an ABCT diverts to the equipment modernization queue to await service
8. Determine equipment modernization queue capacity
9. Determine if an ABCT balks before entering the equipment modernization queue
10. Determine if an ABCT enters the queue after a balk decision point occurs
11. Determine if an ABCT reneges while waiting for service in the queue
12. Determine if an ABCT remains in the queue after a renege decision point occurs
13. Determine if an ABCT qualifies for induction to an equipment modernization line from its position in the queue

The flowchart in Figure 3 and its supporting algorithm provide a general overview of the model's behavior. However, a detailed explanation of the subordinate processes that comprise the model in its totality is in order. The step-by-step formulation of the ABCT equipment modernization model follows.

1. Determine and ABCT's Equipment Modernization Completion Status

Executing for period i, the model first determines the modernization cycle completion status μ. A modernization cycle is complete when all ABCTS from the calling population C^0 have completed one iteration of modernization activities. In the instance of modernization cycle completion, the model clears all stored values and commences the next modernization cycle. Otherwise, the model continues to matriculate ABCTs through the process as depicted by the flow chart in Figure 4.

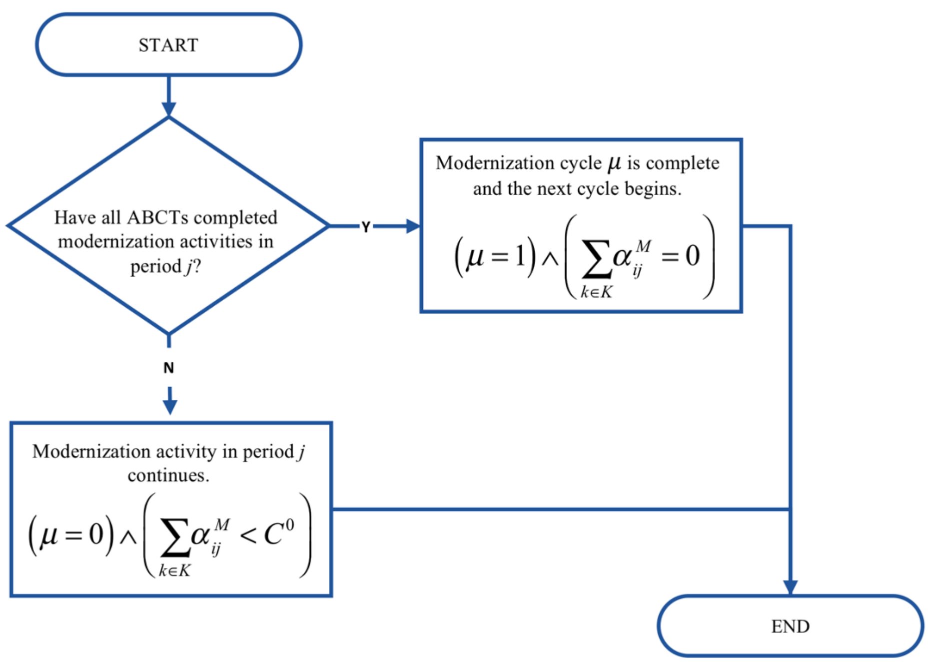

Figure 4. Flowchart for Determining ABCT Completion Status

This report developed the spreadsheet model with several parameters. First, the model observes a maximum calling population $C^0 = 10$ active component ABCTs. This reflects the actual inventory of fully manned armored brigades as of the summer of 2018. The model does not consider the remaining five ABCTs the Army maintains in its reserve component. Secondly, the model evaluates a maximum of 15 equipment modernization cycles over a maximum number of periods also preprogrammed at $j^{\max} = 180$ months. This equates to up to 15 simulated years for each trial of the model run.

2. Determine and ABCT's Consideration for Modernization

The model then considers calling forward an ABCT for participation in the equipment modernization process α_{ij}^{Y}. This is a process, as illustrated by the flowchart in Figure 5, governed by a probability distribution $\varepsilon(x)$ that randomly selects an ABCT from the calling population C^{0} for the first time in period j. The expression for this probability distribution follows.

$$\alpha_{ij}^{Y} = \varepsilon(x) = \begin{cases} 1, & x \le p_{ij}^{Z} \\ 0, & x > p_{ij}^{Z} \end{cases} \tag{12}$$

where

p_{ij}^{Z} = the probability that an ABCT in a given period is considered for equipment modernization,

X = set of random variables; $\{x \mid x \in \mathbb{R}; 0 < x < 1\}$.

As an initial model assumption, all ABCTs in the calling population require modernization. Their randomized consideration simulates the infrequent off-cycle availability of ABCTs to perform non-mission essential tasks such as equipment modernization.

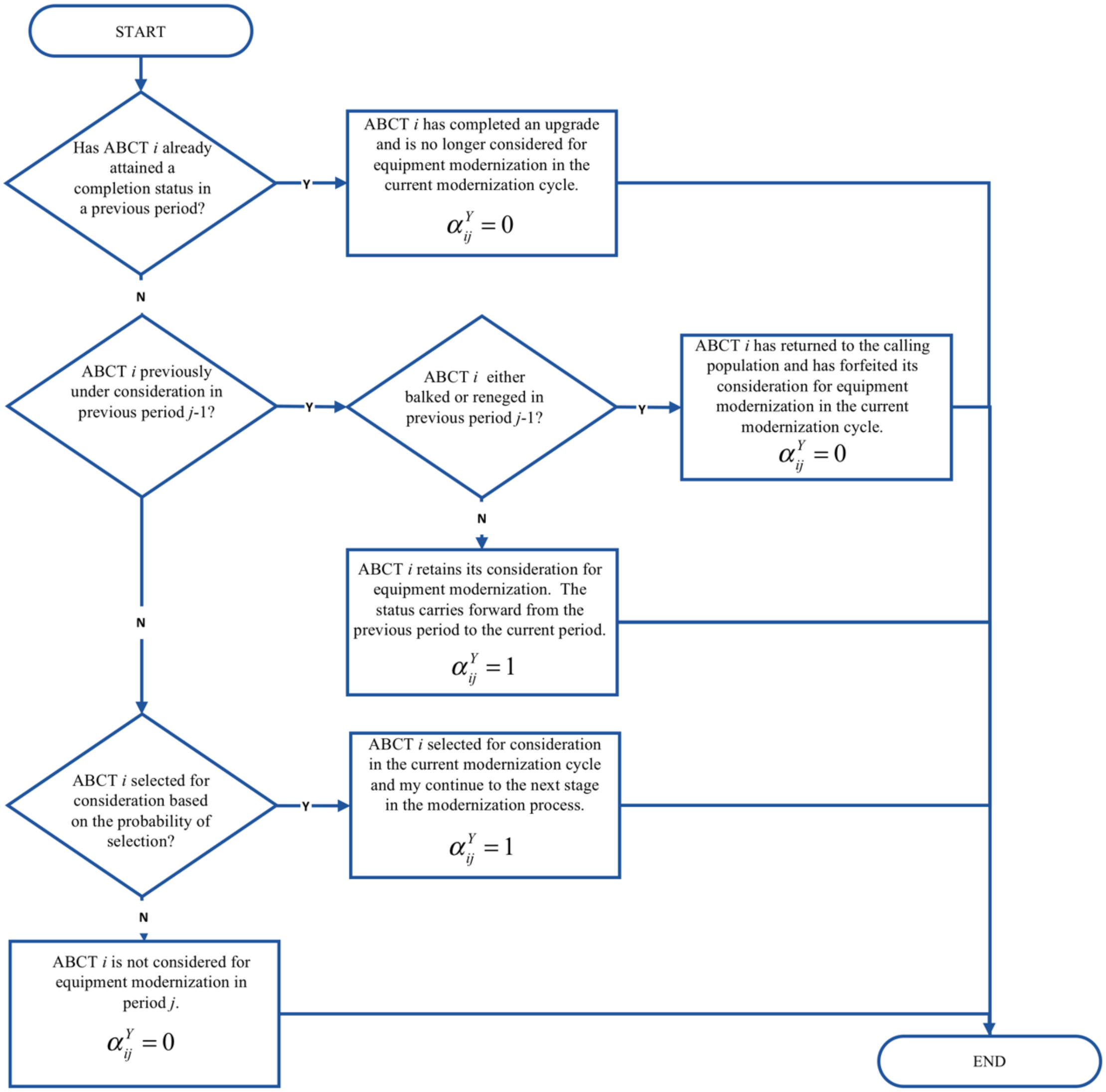

Figure 5. Flowchart for Determining the Consideration for Modernization

3. Determine an ABCT's Window of Availability

The model then assigns a window of availability t^{w} to any ABCT it considers for equipment modernization. Figure 6 exhibits the subordinate process by which the model determines a window of availability based on a probability distribution discussed in Section C of this chapter. The model can assess either a deterministic δ^{w} or stochastic $\sigma^{w}(x)$ window of availability as determined in the scenario calibration stage. Fundamentally, this window of availability is the interval of down time than an ABCT can fully commit to equipment modernization activities. The turn-around time between operational missions fluctuates for ABCTs, so the window of availability is a key determinant of an ABCT's ability to participate in a modernization program.

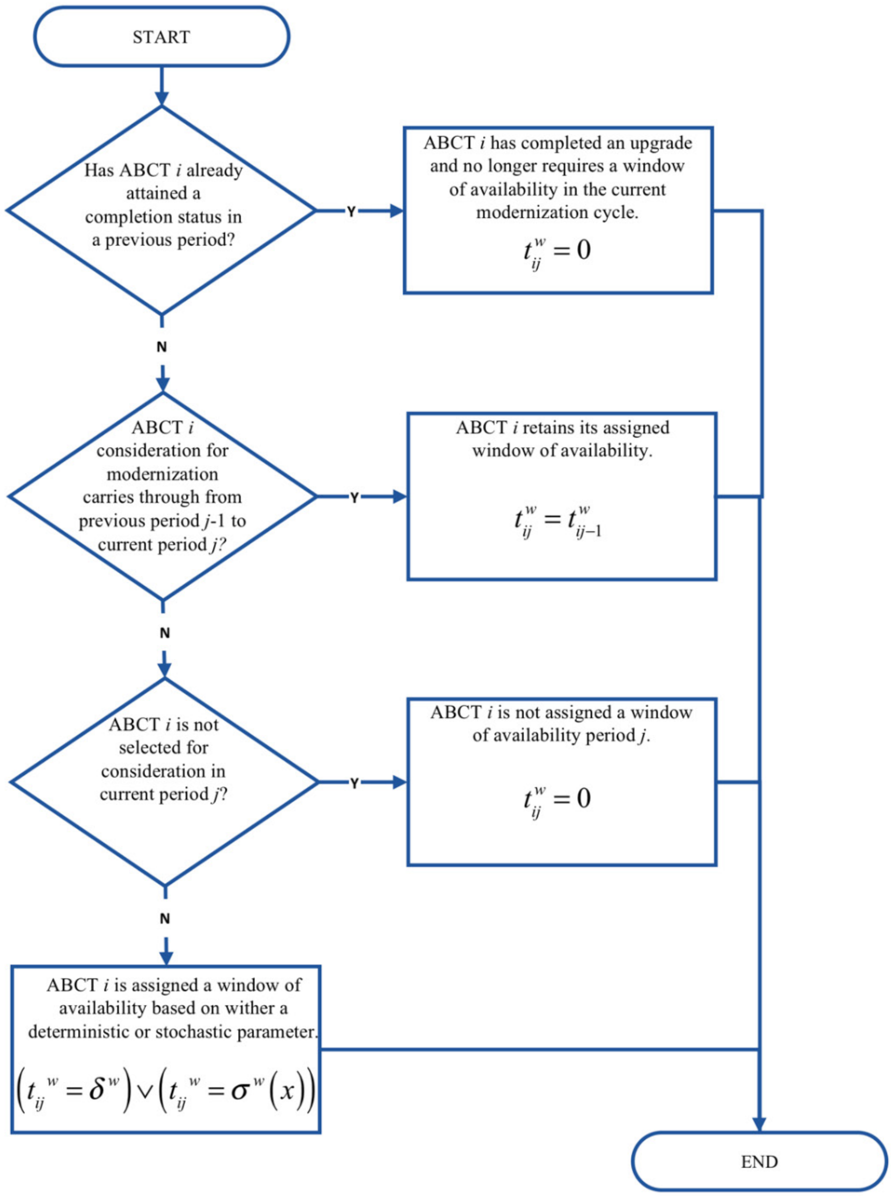

Figure 6. Flowchart for Determining ABCT Windows of Availability

With each successive period, the model advances (decreases) the remaining window of availability τ_{ij}^{w} by a value of one. This accounts for the passage of time and facilitates the rendering of other decisions that pertain to an ABCT's relative positioning within the system. The flowchart in Figure 7 is an illustration of this process.

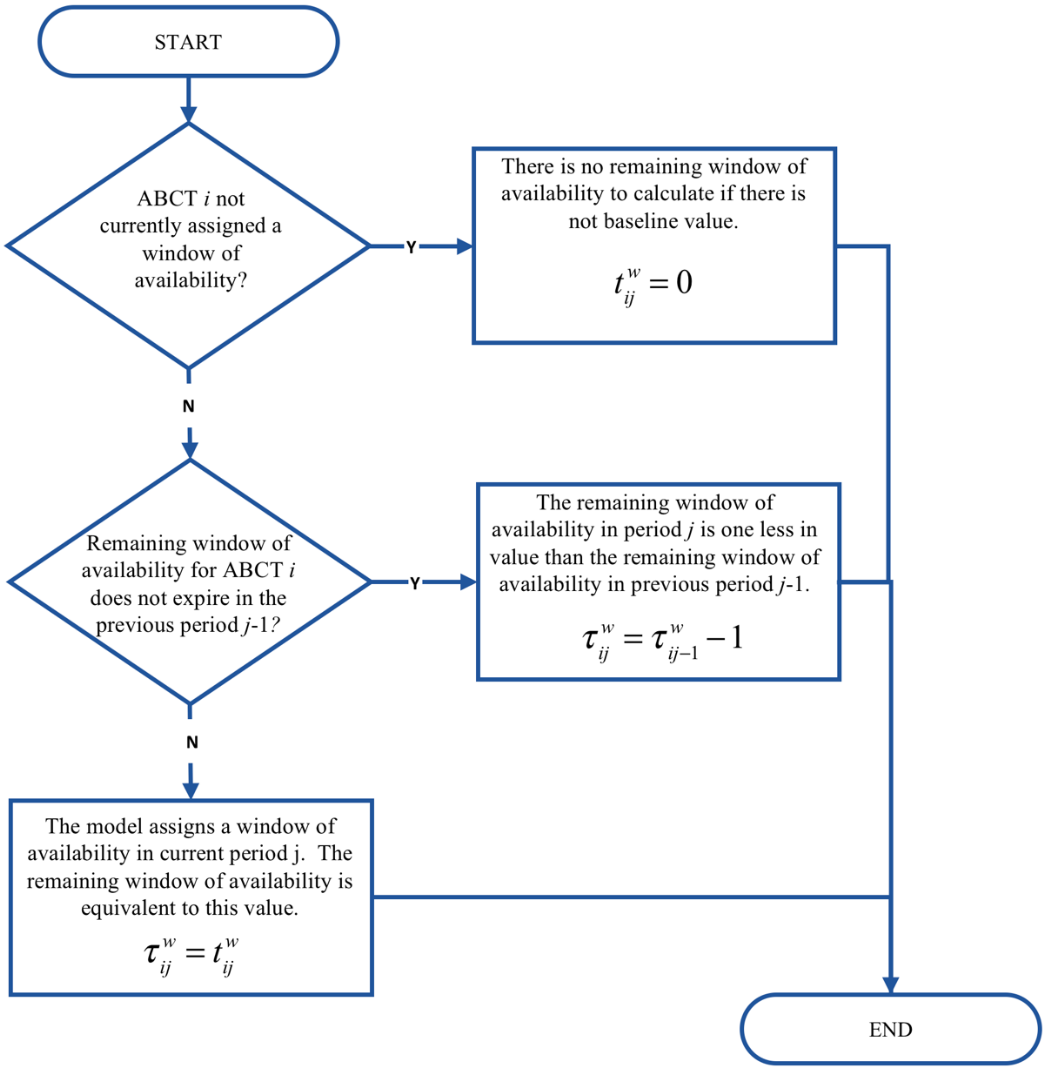

Figure 7. Flowchart for Determining ABCT Remaining Windows of Availability

4. Determine Materiel Fielding Team Service Capacity

The model then considers the number of fielding teams v_j available at the beginning of the current period j to conduct equipment modernization activities. The flowchart in Figure 8 is generalizes the formulation the model used to determine the number of fielding teams.

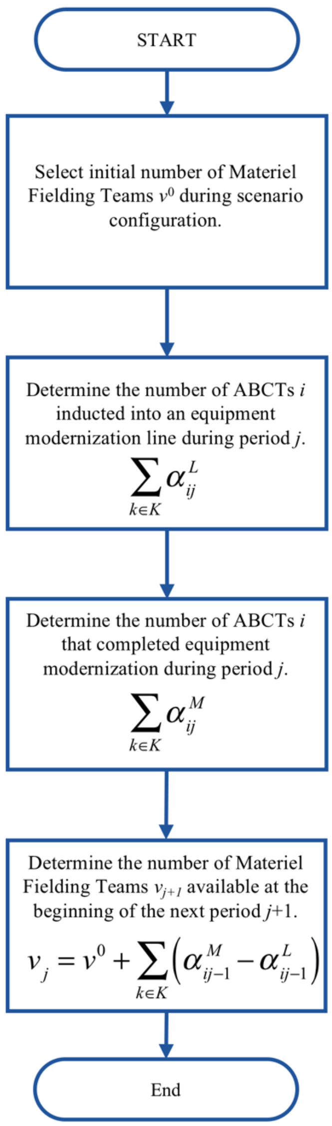

Figure 8. Flowchart for Determining Materiel Fielding Team Service Capacity

When the model allocates all of its materiel fielding teams to provide service, the fielding team shortage will trigger an ABCT's decision to join the queue along with other ABCTs awaiting equipment upgrade. If materiel fielding teams are available, then in certain circumstances, the model will immediately induct ABCT i into a modernization program α_{ij}^{L}.

5. Determine Materiel Fielding Team Service Time

If fielding teams are available $v_{ij} > 1$, then the model will provide a randomly determined value for the interval of time t_{ij}^{s} that a fielding team requires to complete an equipment upgrade as shown in Figure 9. This formulation replicates real-world variability in service time caused by factors such as the uncertain availability of serviceable maintenance facilities on a given military installation, extreme whether that constrains activities such as welding and the test driving of vehicles, and equipment throughput impacted by ABCT training schedules.

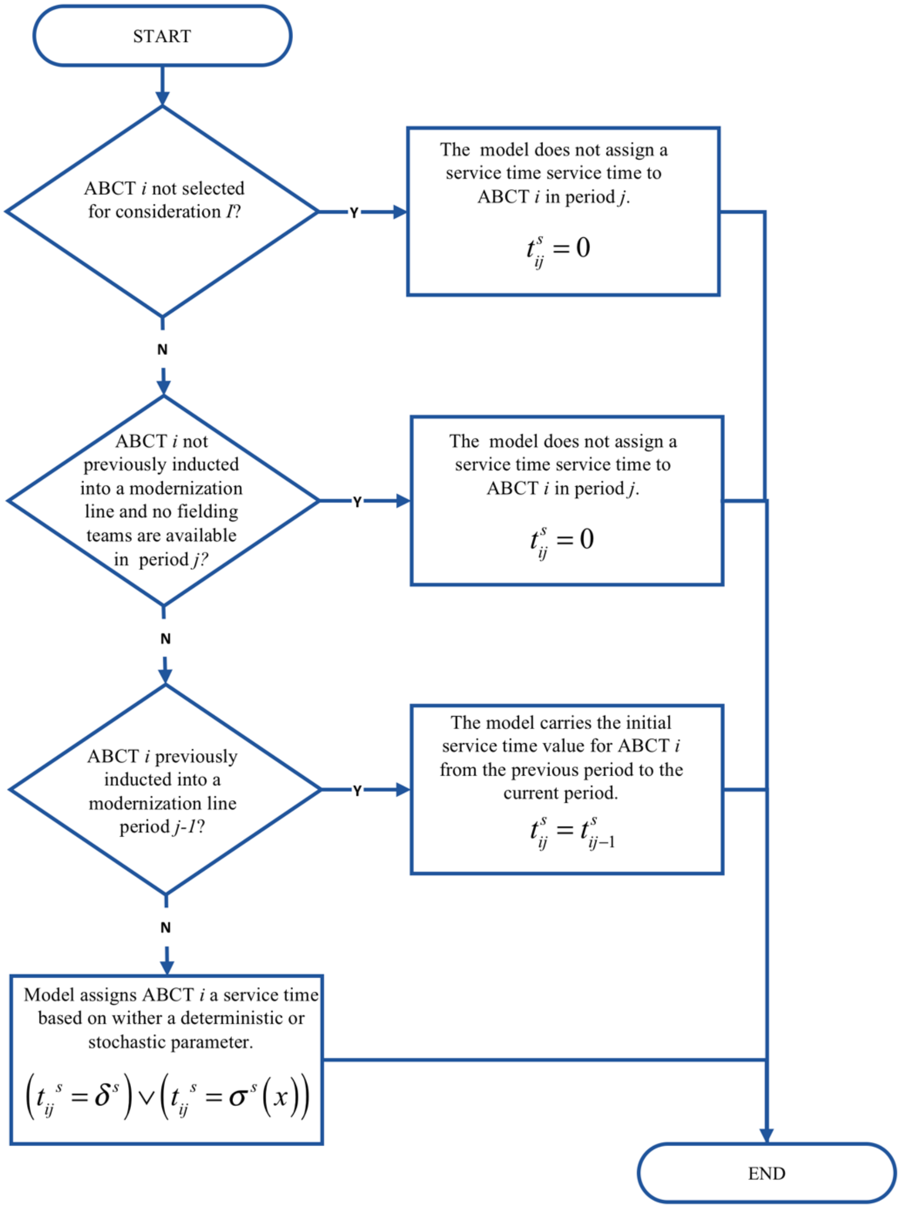

Figure 9. Flowchart for Determining Materiel Fielding Team Service Time

Much like with windows of availability, the model advances (decreases) remaining service time by a value of one with each successive period of time for any period after the model's initial allocation of service time to ABCT i. This reduction to service time occurs only upon an ABCT's induction into a modernization program either directly from the calling population or indirectly from the equipment modernization queue. The flowchart in Figure 10 observes this process.

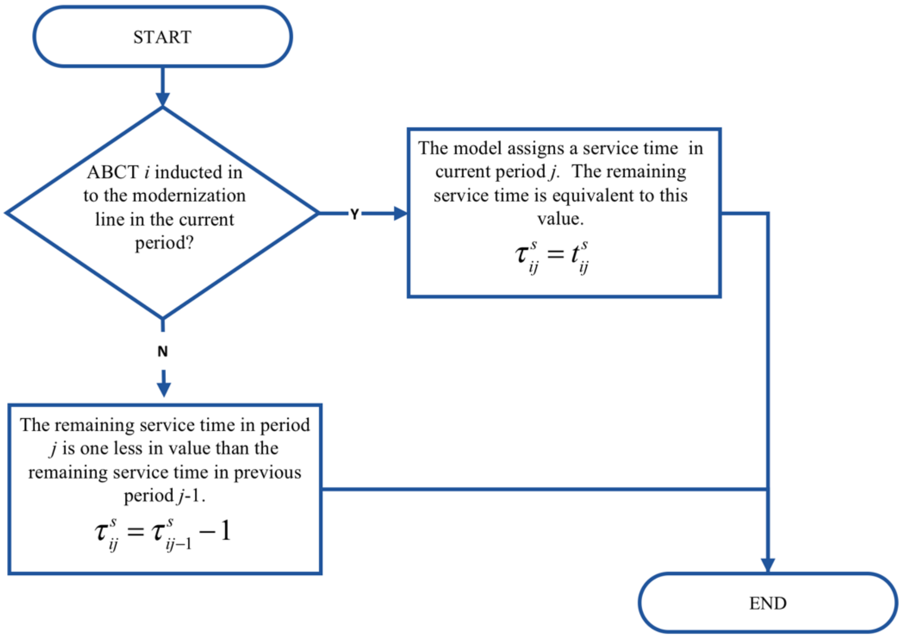

Figure 10. Flowchart for Determining Remaining Service Time

Upon the expiration of the remaining service time t_{ij}^{s}, the model classifies ABCT i as having completed equipment modernization in period j. Depicting this process is the flowchart in Figure 11. The model also removes ABCT i from the calling population of ABCTs that require equipment modernization for the duration of the current modernization cycle.

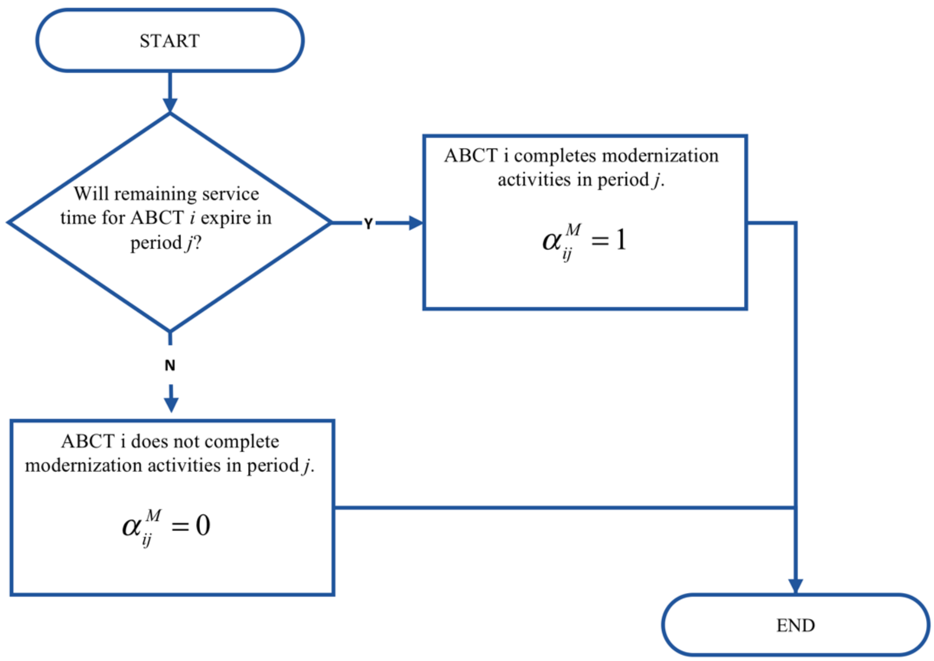

Figure 11. Flowchart for Determining ABCT Modernization Completion Status

6. Determine ABCT Induction Status

Pending both fielding team availability and agreeable service times, the model will induct ABCT i into an equipment modernization line $\alpha_{ij}^{L} = 1$. Once the model inducts an ABCT into a modernization line, it assumes that ABCTs do not prematurely depart before fielding teams complete modernization activities. Consequently, when service time expires τ_{ij}^{s}, ABCT i will complete an upgrade $\alpha_{ij}^{M} = 1$. Figure 12 represents the process via a flowchart.

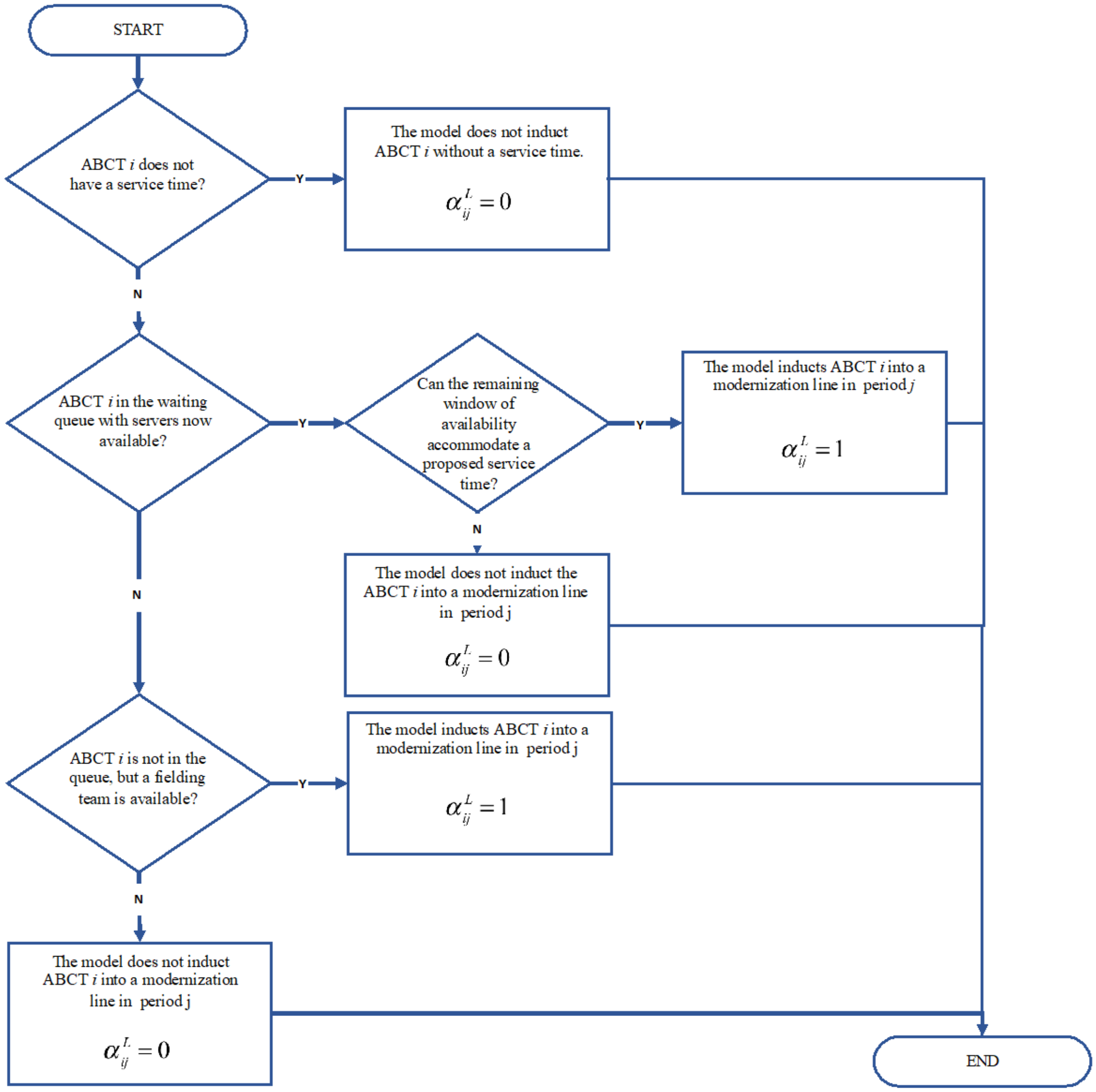

Figure 12. Flowchart for Determining ABCT Induction Status

7. Determine Queue Eligibility Status

Should circumstances preclude ABCT i from immediate induction into an equipment modernization program, the model then declares ABCT i as eligible for entry into the queue α_{ij}^{QE}. This process, as illustrated by the flowchart in Figure 13, is a preliminary stage to formal entry into the equipment modernization queue. Formal entry into the queue occurs following the balk decision cycle by ABCT i.

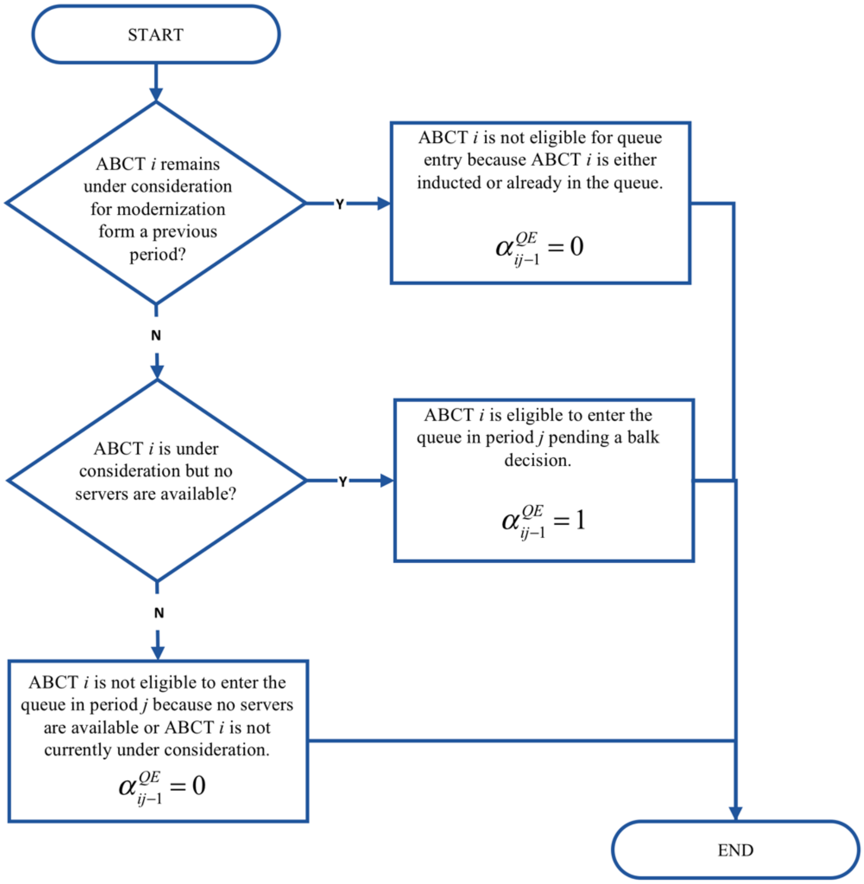

Figure 13. Flowchart for Determining ABCT Queue Eligibility Status

8. Determine Queue Capacity

The model then considers the available queue capacity q_j of the system in the current period j. The modernization process involves a finite and relatively small population of ABCTs that must fulfill world-wide operational demand. The number of ABCTs that could participate in equipment modernization activities fundamentally constrains the system's maximum queue capacity. The flowchart in Figure 14 provides an overview of the model's evaluation of its queue capacity.

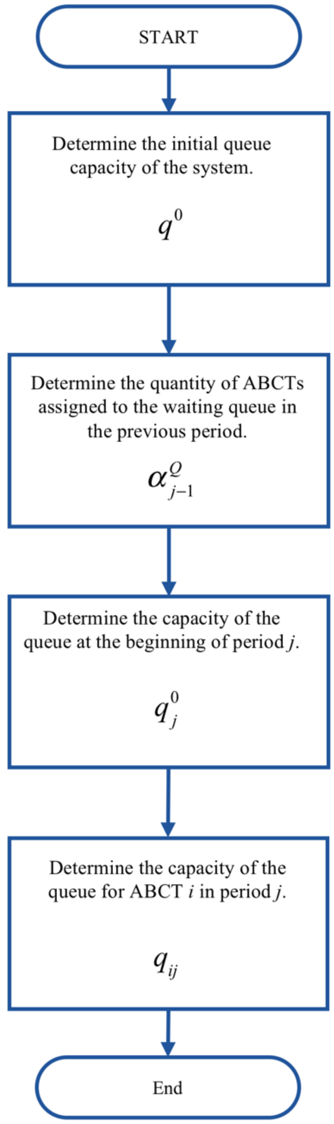

Figure 14. Flowchart for Determining Queue Capacity

The model derives the system's overall initial queue capacity $\boldsymbol{q}^{\mathbf{0}}$ from the selection of independent variables during the calibration of a modeling scenario. The model utilizes $\boldsymbol{q}^{\mathbf{0}}$ as the basis for determining the initial queue capacity in each period $\boldsymbol{q}_j^{\mathbf{0}}$ and for each ABCT $\boldsymbol{q}_{ij}$. The analytic expression of queue capacity $\boldsymbol{q}_{ij}$ for ABCT $\boldsymbol{i}$ follows.

$$q^0 = \begin{cases} g - v^0, & h > v^0 \\ 0 \quad , & h = v^0 \end{cases} \tag{13}$$

$$\alpha_{j-1}^{Q} = \sum_{k \in K} \left(\alpha_{ij-1}^{QR} - \alpha_{ij-1}^{IQ} \right) \tag{14}$$

$$q_j^0 = q^0 - \alpha_{j-1}^{Q} \tag{15}$$

$$q_{ij} = \begin{cases} q_j - 1, & q_j^0 \geq 1 \\ 0, & q_j^0 = 0 \end{cases} \tag{16}$$

where

v^0 = independent variable for the initial number of fielding teams,

g = the number of ABCTs not required to conduct enduring commitments,

h = the number of ABCTs not required to conduct enduring commitments or contingency,

q^0 = initial queue capacity for the equipment modernization process,

α_{j-1}^{Q} = number of ABCTs in the queue during the previous period $j-1$,

α_{ij-1}^{QR} = post-renege queue status for ABCT i in the previous period $j-1$,

α_{ij-1}^{IQ} = queue induction status for ABCT i in the previous period $j-1$,

q_j^0 = initial queue capacity in the current period j,

q_j = queue capacity at any given moment in period j,

q_{ij} = queue capacity assessed by ABCT i before a balk decision.

9. Determine ABCT Balk Decision

The model will cause an ABCT to balk $\alpha_{ij}^{B} = 1$ before ever entering the queue if the queue is full to capacity. Balking occurs when the model initially assigns a service time t^s of greater value than the window of availability t^w for ABCT i. It also occurs when the model allocates a 1-month window of availability in the absence of available servers. This balking behavior replicates an ABCT commander's decision to defer modernization activities to a later date. It also replicates a decision from higher echelons of command to reprioritize modernization efforts from one ABCT to another.

In any event, the outcome results in the forfeiture of an opportunity for ABCT i to receive an equipment upgrade in its originally planned window of availability. A balk constitutes an ABCT's exit from the equipment modernization process and return to the calling population for consideration in a later period. Figure 15 illustrates the process flowchart for this activity.

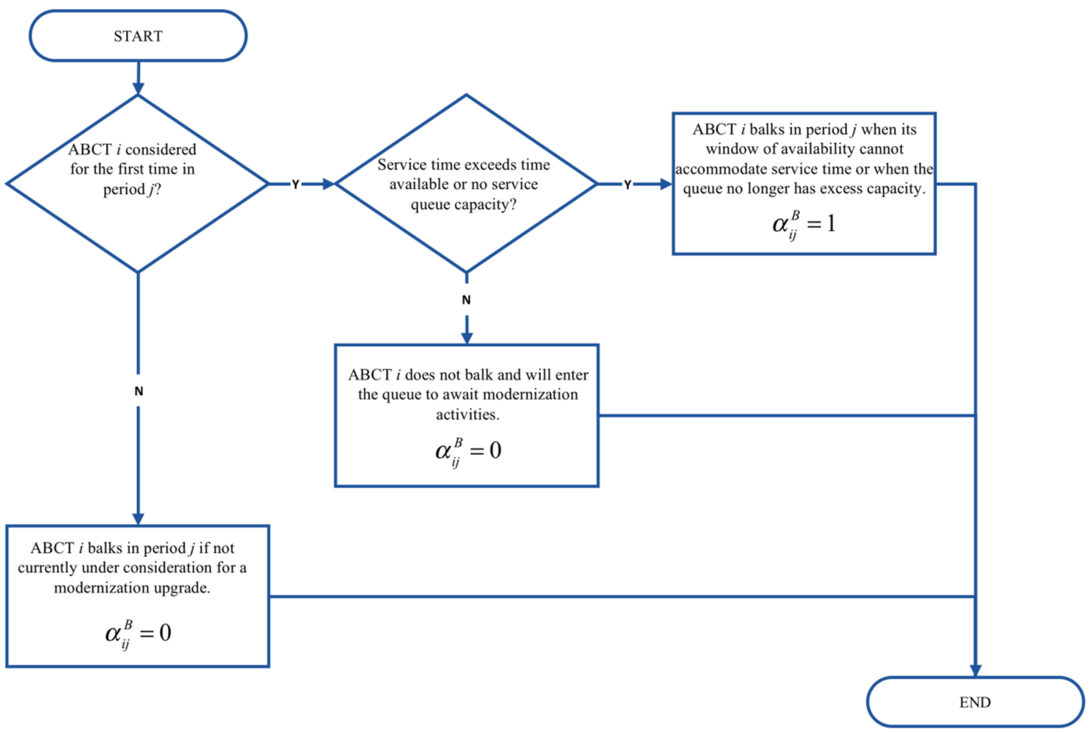

Figure 15. Flowchart for Determining ABCT Balk Decision

10. Determine Post-Balk Queue Position

If ABCT i does not balk $\alpha_{ij}^{B} = 0$, then the model will progress an ABCT to the queue α_{ij}^{QB} where it will await the next available fielding team. The flowchart in Figure 16 demonstrates this process.

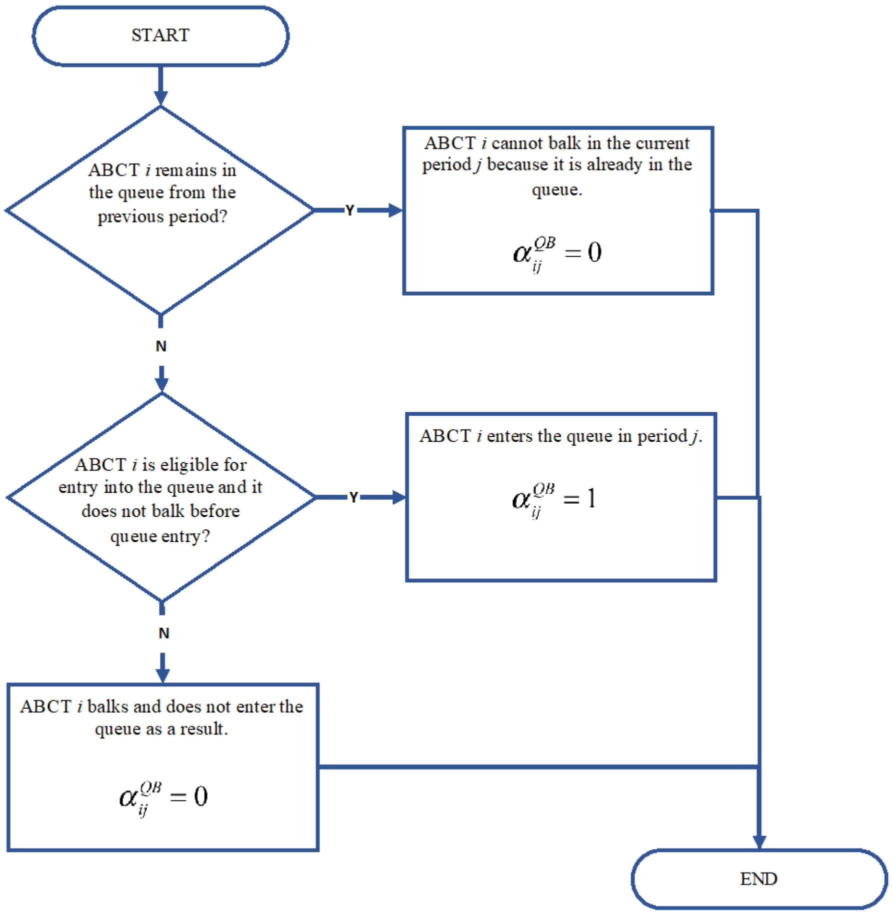

Figure 16. Flowchart for Determining ABCT Post-Balk Queue Position

11. Determine ABCT Renege Decision

As an ABCT's remaining window of availability τ_{ij}^{w} closes, the likelihood of its induction into a modernization program decreases as well. Consequently, the model only provides ABCT i with one opportunity to find a fielding team match from its position in the queue. ABCT i forfeits its queue position by reneging α_{ij}^{R}. This occurs if its available window t^{w} disagrees with the service time t^{s} expressed by an available fielding team. Reference Figure 17 for the corresponding flowchart. A renege also constitutes an ABCT's exit from the equipment modernization process and return to the calling population for future consideration.

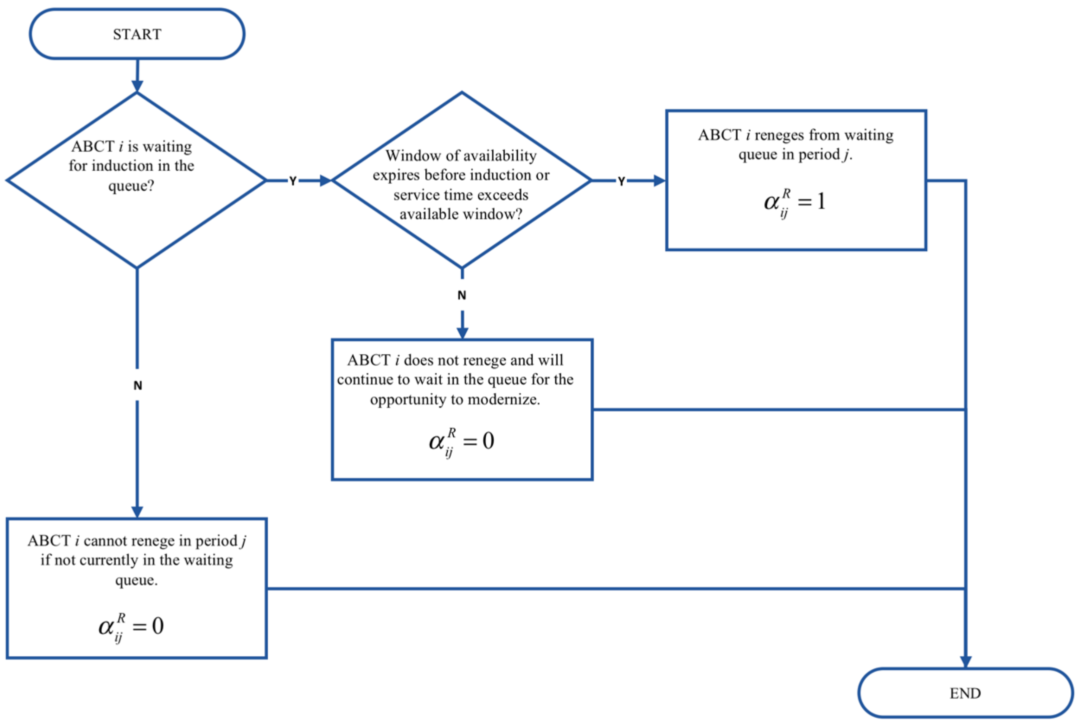

Figure 17. Flowchart for Determining ABCT Renege Decision

12. Determine Post-Renege Queue Position

The model will progress ABCT i through the queue α_{ij}^{QR} in successive periods until the model influences a renege or induction decision. ABCT i will ultimately renege, as the flowchart demonstrates in Figure 18, if the model has not inducted it into a modernization program before the ABCT's remaining window of availability expires.

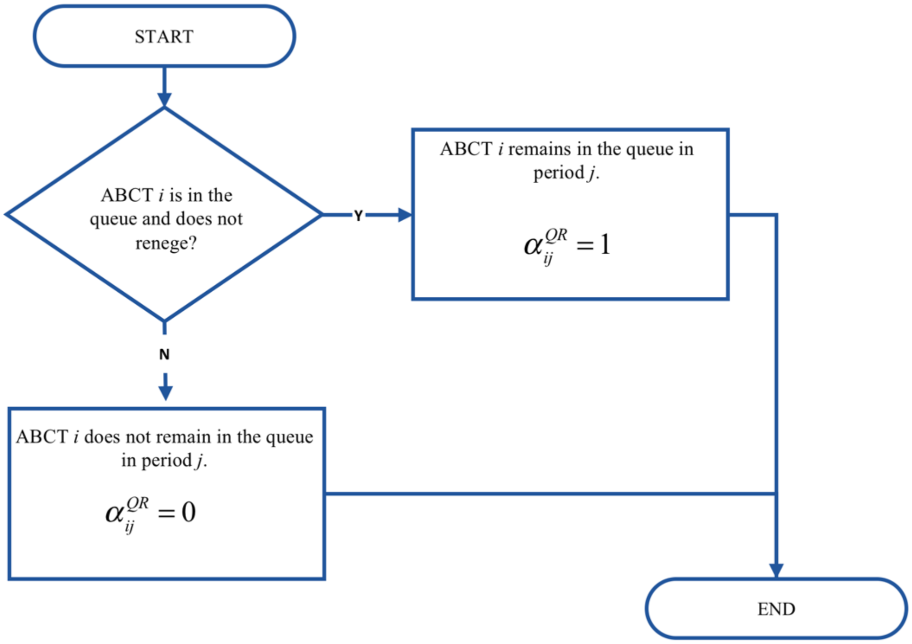

Figure 18. Flowchart for Determining ABCT Post-Renege Queue Position

13. Determine Induction Status from Queue Position

When a fielding team becomes available and the ABCT's remaining window of availability τ_{ij}^{w} and fielding team service time t_{ij}^{s} agree, the model will induct ABCT from the queue α_{ij}^{IQ}. ABCT i will complete modernization activities at the expiration of its service time τ_{ij}^{s}. If, however, service time is less than the remaining window of availablity for ABCT i, then ABCT i will renege. The flow chart in Figure 19 depicts this process.

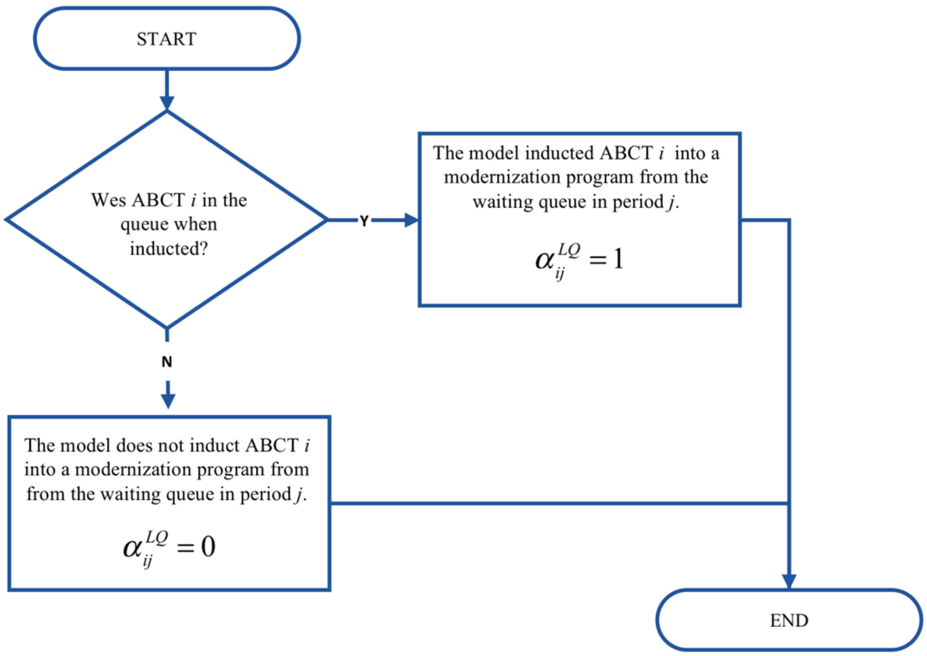

Figure 19. Flowchart for Determining Induction Status from Queue Position

F. CALCULATION OF DEPENDENT VARIABLE

Modernization cycle time t_{μ}^{c} as interpreted by the model is the measure of how long the modernization process takes the Army to complete one increment of equipment upgrades for its entire inventory of ABCTs C^{0}. In the context of an ABCT's primary warfighting platforms, this cycle time is in actuality a measure of how quickly the Army can provide a suite of upgrades to its entire fleet of tanks, infantry fighting vehicles, and self-propelled howitzers.

The first modernization cycle originates at the beginning of period $j = 1$, the first period, no matter if the model has inducted ABCT i into an equipment modernization program $\alpha_{ij}^{L} = 1$. This first modernization cycle μ ends and the second cycle $\mu + 1$ begins when the final ABCT from the calling population completes modernization activities $\alpha_{ij}^{M} = 1$. This pattern continues for all subsequent modernization cycles.

One technique the model uses to capture these start and end times is to simply tabulate the elapsed completion time ρ_μ of each modernization cycle μ^βrelative to the period $j = 1$. The model derives the average equipment modernization cycle time t^ζ from the average of elapsed cycle time differences. The expressions for these calculations follow.

$$\mu^\beta = 1 \tag{17}$$

$$\mu^\phi = \sum_{\mu \in M} \mu^\beta \tag{18}$$

$$t_\mu^c = \rho_\mu - \rho_{\mu-1} \tag{19}$$

$$t^\zeta = \frac{\sum_{\mu \in M} t_\mu^c}{\mu^\phi} \tag{20}$$

where

μ^β = modernization cycle completion status,

μ^ϕ = number of completed modernization cycles,

ρ_μ = elapsed completion time for equipment modernization cycle μ,

t_μ^c = modernization cycle time,

t^ζ = average cycle time for all modernization cycles μ.

V. SIMULATION AND ANALYSIS

A. INTRODUCTION

This chapter discusses the simulation of a range of ABCT equipment modernization scenarios. This report consolidates the modeled scenarios into four cases for the purposes of statistical analysis.

B. SIMULATION SETUP

This report utilized the Microsoft Excel What-If Analysis data table function to conduct a 50-trial Monte Carlo simulation of 855 discrete model scenarios. This simulation generated 42,750 total lines of data that this report utilized to interpret the ABCT equipment modernization process. Each model scenario represents one unique combination of independent variables given the initial set of model parameters. These initial parameters stipulate that the model will assess ten active component ABCTs over a maximum 180 observed periods. The definitions for the parameters follow.

1. Sets

D Set of enduring ABCT commitments to deploy; $\{3,4,5\}, d \in D$

R Set of readiness levels (percentage); $\{0.6,0.7,0.8\}, r \in R$

T Set of units of time (months); $\{1,\ldots,21\}, t \in T$

V Set of Materiel Fielding Teams; $\{1,\ldots,5\}, v \in V$

2. Base Case Scenarios

All subsequent analysis of the simulation results will utilize the base case as a point of reference. This base case includes the range of input values when both windows of availability and service times are unpredictable in duration. The model replicates these unpredictable intervals of time by using a distribution of values that the model applies stochastically.

3. Test Case Scenarios

The initial parameters limit the simulation of model scenarios to those that exist within the realm of operational feasibility and practicality. The report categorizes these scenarios into three test cases that explore the effect of implementing different combinations of deterministic and stochastic values for windows of availability and service time. All other independent variables remain equal in each case. Test Case 1 includes all trails that pertain to stochastic windows of availability and deterministic service times. Test Case 2 groups trials involving deterministic windows of availability and stochastic service times. Finally, Test Case 3 consolidates all scenarios with both deterministic windows of availability and service time.

C. STATISTICAL RESULTS

This report utilized Microsoft Excel's Data Analysis ToolPak add-in to facilitate the statistical analysis of the simulated data.

1. Base Case

The base case for ABCT equipment modernization process captures a fluid operating environment in which ABCT availability and fielding team service times are non-standard and situationally dependent. This is reflective of the intensively managed coordination of efforts that actually align an ABCT's non-mission status with the available capacity of a fielding team to apply an equipment upgrade.

The average modernization cycle time for the base case was 30.43 months (SD = 11.07). Modernization cycle time for the base case ranged from 0 to 85.5 months (M = 30.43, SD = 11.07). The skewness of modernization cycle time was .918 (SE = .052), with a kurtosis of .577 (SE = .103). The low cycle time of 0 was a single outlier trial of a scenario involving an enduring commitment of 2 ABCTs, a readiness level of 60%, and a fielding team quantity of 1. This return was a consequence of stochastic windows of availability that were perpetually less than the stochastic service times generated by the model. This reflects the reality that equipment modernization is not feasible if ABCT availability cannot accommodate lengthy service times.

This report calculated a multiple linear regression to assess the degree that the model's five independent variables impact the variance of ABCT equipment modernization cycle time. A significant regression equation was found ($F(5,2244) = 1178.183$, $p < .001$), with an R^2 of 0.724). The regression model coefficients for the base case demonstrate the unit-change impact of the model's independent variables on modernization cycle time.

However, each independent variable's t-statistic normalizes this unit-change impact relative to the unit of measure of the dependent variable. Of the five independent variables, the number of fielding teams ($t=-55.65$, $p < .001$) and the readiness level ($t = 39.93$, $p < .001$) are the two most significant predictors of modernization cycle time.

The correlation of these two independent variables and the average modernization cycle time are significantly correlated at an alpha level of .05. The model demonstrates a negative relationship between the number of fielding teams and modernization cycle time, ($r(2249) = -.68$, $p < .001$). The relationship between readiness levels and modernization cycle time is positive ($r(2249) = .43$, $p < .001$).

2. Test Case 1

With this test case, the operating environment remains fluid, but is one in which the Army mandates a policy that standardizes fielding team service times as a means to apply some level of uniformity to the equipment modernization process. Unlike the base case, Test Case 1 assumes the U.S. Army has mandated a policy that standardizes fielding team service times in an effort to influence the modernization process. Generally, cycle times on the higher end of the range involve a low number of fielding teams and a 6-month interval for service time

The average modernization cycle time for Test Case 1 was 36.82 months (*SD* = 19.79). Modernization cycle time ranged from 10.4 to 178 months (*M* = 36.82, *SD* = 19.79). The skewness of modernization cycle time for Test Case 1was 1.62 (*SE* = .026), with a kurtosis of 3.72 (*SE* = .052).

A multiple linear regression of the simulated results predicts the average ABCT equipment modernization cycle time based on the model's five independent variables. A significant regression equation was found (F(5,8999) = 5407.29, $p < .001$), with an R^2 of 0.75. As observed by the regression model, the number of fielding teams (t = -88.25, $p < .001$) and the service time (t = 55.39, $p < .001$) are the two most significant predictors of modernization cycle time.

The correlation of each of these two independent variables and the average modernization cycle time are significantly correlated at an alpha level of .05. The relationship between the number of fielding teams and modernization cycle time is negative (r(8999) = -.56, $p < .001$). The model demonstrates a positive relationship between service time and modernization cycle time, (r(8999) = .59, $p < .001$).

The deterministic service times observed by the model are integer values ranging from 3 to 6 months. However, the expected value of stochastic service times as determined by the cumulative probability distribution is 4.129 months. Of the 26 observations in this probability distribution, 19 of them were less than 5 months. Limiting the range of deterministic service times from 3 to 4 in Test Case 1 accounts for this skewness. The relative importance of the number of fielding teams and the readiness level to the variance of equipment modernization cycle time does not change. However, the mean cycle time changes from 36.82 months (SD = 19.79) to an average of 26.88 months (*SD* = 10.85).

3. Test Case 2

Test Case 2 evaluates scenarios with deterministic windows of availability and stochastic service times, with all other variables remaining the same. This tests the situation in which the Army can more predictably manage operational demand and prescribe standardized intervals of down-time between known operational missions.

The average modernization cycle time for Test Case 2 was 35.26 months (*SD* = 15.97). This modernization cycle time ranged from 12.92 to 176 months (M = 35.26, *SD* = 15.97). The skewness of modernization cycle time was 1.92 (*SE* = .026), with a kurtosis of 7.82 (*SE* = .052).

A multiple linear regression of the simulated results predicts the average ABCT equipment modernization cycle time based on the model's five independent variables. This report found a significant regression equation ($F(5,8999) = 2606.18$, $p < .001$), with an R^2 of 0.59. As observed by the regression model, the number of fielding teams ($t = -55.57$, $p < .001$) and the readiness level ($t = 62.55$, $p < .001$) are the two most significant predictors of modernization cycle time.

The correlation of each of these two independent variables and the average modernization cycle time are significantly correlated at an alpha level of .05. The relationship between the number of fielding teams and modernization cycle time is negative ($r(8999) = -.42$, $p < .001$). The model demonstrates a positive relationship between readiness level and modernization cycle time, ($r(8999) = .41$, $p < .001$).

A key assumption of this model is that the modernization process does not occur in instances when ABCT windows of availability are less than the expected service time of a modernization activity. The full range of deterministic windows of availability observe during the simulation included integer values between 3 to 6 months. If the expected value of service time is 4.129 months, then it follows that deterministic windows of availability must be equal to or greater than 4.129 months. Limiting the deterministic windows of availability to include only 5- and 6-months accounts for this inefficiency. The relative importance of the number of fielding teams and the readiness level to the variance of equipment modernization cycle time does not change. However, the mean cycle time modernization cycle time decreased from 35.26 months (*SD* = 15.97) to 29.52 months (*SD* = 10.9).

4. Test Case 3

This Case eliminates the variability of time intervals altogether by presupposing that the Army can execute definitive control over both ABCT windows of availability and fielding team service time. The variability of cycle times within a given scenario in this model is strictly a consequence of an ABCTs probability of consideration for service vice any combination of stochastic variables and the probability that an ABCT enters the equipment modernization process.

The average modernization cycle time for Test Case 3 was 29.15 months (*SD* = 14.27). Modernization cycle time ranged from 9.47 to 121 months (*M* = 29.15, *SD* = 14.27).

The skewness of modernization cycle time was 1.47 (SE = .016), with a kurtosis of 2.02 (*SE* = .033).

A multiple linear regression of the simulated results predicts the average ABCT equipment modernization cycle time based on the model's five independent variables. Tis report found a significant regression equation ($F(5,22499) = 12455.17$, $p < .001$), with an R^2 of 0.74. As observed by the regression model, the number of fielding teams ($t = -213.49$, $p < .001$) and service time ($t = 97.69$, $p < .001$) and are the two most significant predictors of modernization cycle time.

The correlation of these two independent variables each possess with the average modernization cycle time are significantly correlated at an alpha level of .05. The relationship between the number of fielding teams and modernization cycle time is negative ($r(22499) = -.733$, $p < .001$). However, the model demonstrates a positive relationship between service time and modernization cycle time, ($r(22499) = .37$, $p < .001$).

Test Case 3 observes deterministic windows of availability and deterministic service times that both range between integer values of 3 to 6 months. Constricting deterministic windows of availability to 5 and 6 months while concurrently constricting deterministic service times to 3 and 4 months is an example of the U.S. Army's strict control of the modernization process. These restrictions could theoretically decrease modernization cycle time from 29.15 months (*SD* = 14.27) to 26.12 months (SD = 11.04).

D. ANALYSIS

The statistical results of the simulation suggest that the number of fielding teams, the readiness level, and the fielding team service time are the primary determinants of cycle time variance. While the importance of the number of fielding teams is relatively high in each of the four cases, the same does not hold true for the other two variables. The readiness level more so than service time influences modernization cycle time to a higher degree when service times are stochastic. Conversely, the opposite is true when the model observes deterministic service times. In these scenarios, service time had a greater influence than the readiness level.

1. The Number of Materiel Fielding Teams

With the exception of Case 3, the number of fielding teams is the one independent variable that has the most influence on the variability of equipment modernization cycle time. Its correlation coefficient in the base case as well as in Test Cases 1 and 2 were moderately to considerably strong with coefficient absolute values well in excess of 0.5.

The strong negative correlation implies that cycle time decreases with the increase in fielding teams no matter the statistical influence of the other four independent variables. This trend also holds true with adjustments that constrict the target ranges of deterministic windows of availability and cycle times. Furthermore, the t-statistics indicate that the number of fielding teams is the preeminent independent variable that influences the variability of modernization cycle time.

However, the implications of diminishing returns should temper the carte blanche employment of the maximum number of fielding teams available. In terms of overall cycle time reduction, the prudent course of action for the U.S. Army is to maintain a constant employment of two Materiel Fielding Teams with the ability to flex to a third fielding team as appropriate.

Utilizing a second fielding team results in a 34.6% reduction in the equipment modernization cycle time. Table 5 illustrates the calculated marginal impact to the reduction of modernization cycle time of each additional fielding team.

Table 5. Fielding Team Diminishing Returns

Fielding Team	2	3	4	5
		Percentage Change		
Base Case	-32%	-17%	-7%	-4%
Test Case 1	-37%	-18%	-9%	-7%
Test Case 2	-29%	-13%	-4%	-2%
Test Case 3	-40%	-22%	-13%	-8%
Average	**-34.6%**	**-17.5%**	**-8.3%**	**-5.3%**

2. Readiness Level

If observed in isolation, the readiness level in neither of the four cases has a particularly strong correlation coefficient. All correlation coefficient values were all less than 0.5. Though the linear relationship between the readiness level and equipment modernization cycle time is generally weak, the regression model t-scores indicate that this independent variable contributes considerably to the variability of modernization cycle times generated by the simulation.

Since the correlation coefficient and t-statistic are positive for this variable in all four cases, the increase in the readiness level amounts to an increase in modernization cycle time. This is a logical conclusion because as the readiness level increases, the number of ABCTs available to perform modernization activities at any one time decreases. This inhibits the throughput of ABCTs in the modernization process and each cycle takes longer to complete for the lack of availability.

3. Fielding Team Service Time

Test Cases 1 and 3 impose deterministic values for service time. In both cases, the t-statistic for service time indicate that the variable has some degree of influence to the variability of equipment modernization cycle time. However, for either case, the linear correlation of service time and equipment cycle time are positive, but below 0.5. Nevertheless, longer service times intuitively portend to a longer modernization cycle time. The relative influence of deterministic service time, however, is secondary to another variable. In Test Cases 1 and 3, the superseding variable is the number of fielding teams.

The Base Case and Test Case 2 pertain to stochastic service times. Stochastic service times have little to marginal statistical influence on the variability of ABCT equipment modernization cycle time.

VI. RECOMMENDATIONS AND CONCLUSION

A. RECOMMENDED COURSE OF ACTION

The challenge faced by the U.S. Army and its inventory of ABCTs is in finding the balance between fulfilling all operational imperatives while simultaneously perpetuating a capability overmatch against a threat with advancing warfighting capacity. Compounding the issue is the complexity of the multi-domain operating environment, constraints to fiscal resources, and the perpetual uncertainty of the demand for armored forces such as ABCTs.

In the interest of a more expeditious modernization cycle time for ABCT equipment, this report offers two policy recommendations. First, the U.S. Army could standardize the maximum fielding team service time to no more than four months. Secondly, the U.S. Army should employ only two to three materiel fielding teams in support of major equipping programs for ABCTs. Enacting these two policy recommendations could theoretically reduce the average modernization cycle time for 10 ABCTs from 30.43 months ($SD = 11.07$) to 22.51 months ($SD = 5.68$).

B. RECOMMENDATIONS FOR FURTHER RESEARCH

This model, as a representation of dynamic Army force management and materiel acquisition processes, is fairly simplistic. By no means does it capture the layers of complexity that account for exigencies such as budget reprioritization, manning shortfalls, and no-notice contingency operations among other things. Accounting for these types of uncertainty could possibly require developing the model with simulation software more robust than Microsoft Excel.

Furthermore, the model only addresses the U.S. Army's ten Active Component ABCTs in isolation. Additional spreadsheet formulation is necessary to examine the process for the entire inventory of ABCTs to include the U.S. Army's five reserve component ABCTs and any unmanned ABCT sets of equipment stored in prepositioned stocks around the world. The variables that control the availability of the equipment within these other organizations significantly differ than the variables that exist for active component ABCTs.

Within the scope of the spreadsheet model, however, there are several aspects of the model as a general queueing application that merit further investigation. Of foremost interest is the configuration of the model to account for different service disciplines. As currently developed, the model executes as a service in random order (SIRO) as opposed to a first-in, first-out (FIFO) or as a last-in, first-out (LIFO) queueing system. Secondly, the model currently does not collect statistical data pertaining to either server or queue utilization. The information gleaned from these data is necessary to support resourcing decisions.

Lastly, the utility of this report's spreadsheet model of a machine interference problem would improve if its underlying spreadsheet formulation could optimize the use of simulation software. The key impediment to the model's ability to fully integrate with Oracle Crystal Ball is the method that the model uses to assign random intervals of time. Whereas the spreadsheet model uses a random number to call for a specific value from a cumulative distribution table on a per-customer basis, Crystal Ball applies values for modeling forecasts on a per-trial basis. Consequently, Crystal Ball can only simulate deterministic values for windows of availability and service time. It cannot do the same for stochastic time intervals. Solving this incongruity would significantly expedite the task of simulating the panoply of modeling scenarios.

C. CONCLUSION

This report interpreted the ABCT equipment modernization process as a finite population, multi-server machine interference problem and developed a spreadsheet model to replicate the process. Critical to the development of the model was the replication of decision points to mimic ABCT balking or reneging from the equipment modernization process.

With specific emphasis on five independent variables based on Army policy and historical data, the model exists as a simplified representation of the ABCT equipment modernization process. The statistical analysis of simulated scenarios provided insight about the efficacy of enduring operational commitments, the readiness level, ABCT windows of availability, the number of materiel fielding teams, and fielding team service time as they related to the variability of ABCT modernization cycle time.

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