A FURTHER COMPARISON OF DETERMINISTIC AND STOCHASTIC LANCHESTER—ETC(U)

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A FURTHER COMPARISON OF DETERMINISTIC AND
STOCHASTIC LANCHESTER-TYPE COMBAT MODELS.

by

Kurt Dieter Klemm

Sept 1980

Thesis Advisor:

J. G. Taylor

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This thesis examines the differences of deterministic and stochastic LANCHESTER-type combat models. Using an example of square-law attrition, solution methods and solutions are described. A new analytic solution for equal attrition rate coefficients is given. The numerical comparison includes hypotheses about the expected force levels and the variability in the expected force levels as a function of time, initial force levels, and breakpoint force levels.
A Further Comparison of Deterministic and Stochastic Lanchester-Type Combat Models

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ABSTRACT

This thesis examines the differences of deterministic and stochastic LANCHESTER-type combat models. Using an example of square-law attrition, solution methods and solutions are described. A new analytic solution for equal attrition rate coefficients is given. The numerical comparison includes hypotheses about the expected force levels and the variability in the expected force levels as a function of time, initial force levels, and breakpoint force levels.
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I. INTRODUCTION

Combat models are widely used as decision aids in the defense-planning process, at least within the NATO alliance. Current operational combat models are very complex because combat is a very complex process. Unfortunately it is difficult (if not impossible) for the beginner to understand the modelling approaches, concepts and motivation, that may have been used to build such operational models. However, one frequently considers a simple model as a paradigm for the development and understanding of such complex models. This basic approach will be used in this thesis to explore certain issues in the on-going debate about the relative merits of stochastic and deterministic combat models.

A simple model is examined to explore differences between a deterministic and a stochastic approach to a certain type of analytical combat model. As already mentioned, combat is a very complex process, but it is also a complex random process, which can be supported by many examples from military history. Analytical models are abstractions and very often simplifications of reality. It seems to be a legitimate question to ask, what effects the further abstraction of neglecting the randomness in combat may have. At this moment, it should be pointed out that within existing operational analytical models, both stochastic and deterministic models are used.

Previous work done by SPRINGALL [9] and CLARK [4] evolved around theoretical aspects. Their main concern was to give exact analytical solutions and their proofs. CRAIG [5] started to explore the differences
between stochastic and deterministic models more from the numerical point of view, which will be continued in this thesis.

In the next chapter, a deterministic and stochastic version of a differential combat model will be described. The deterministic versions are well-known as LANCHESTER's equations of modern warfare, which were developed in 1914. Combat models, which model attrition from enemy action through a system of differential equations, are usually referred to as LANCHESTER-type models of warfare.
II. THE PARADIGM MODELS

A. THE DETERMINISTIC MODEL

First, LANCHESTER's equations of modern warfare will be briefly reviewed and some simple extensions given.

In 1914 LANCHESTER [7] hypothesized that under "modern conditions" in a combat between two homogeneous forces the firepower of the surviving weapons of one side can be concentrated on the surviving targets of the other side, so that each side's casualty rate is proportional to the number of enemy firers. This can be described by the following equations:

\[ \frac{dx}{dt} = -ay \]  
\[ \frac{dy}{dt} = -bx \]  

with initial conditions

\[ X(0) = x_0 \]  
\[ Y(0) = y_0 \]  

where a is the attrition rate with which the Y-force attrits the X-force, similarly for b. \( x_0 \) and \( y_0 \) are the initial force levels and \( x(t) \) and \( y(t) \) are the force levels at time \( t \). The force levels, as a function of time \( t \), can be written as

\[ x(t) = x_0 \cosh(\sqrt{ab} t) - \frac{\sqrt{a}}{\sqrt{b}} y_0 \sinh(\sqrt{ab} t) \]  
\[ y(t) = y_0 \cosh(\sqrt{ab} t) - \frac{\sqrt{b}}{\sqrt{a}} x_0 \sinh(\sqrt{ab} t) \]  

The state equation relating initial force levels with force levels at some time \( t \) can be derived by dividing (2.1) by (2.2), separating
variables and integrating to yield
\[ b(x_0^2 - x(t)^2) = a(y_0^2 - y(t)^2). \] (2.7)

This form of the state equation explains why this model is also referred to as the "square-law" attrition process. WEISS [11] has given a set of assumptions under which LANCHESTER's equations for modern warfare may apply:

A1.) Two homogeneous forces are engaged in combat. Every unit on a particular side has the same capabilities. The attrition rate may be different for the two forces.

A2.) Each unit on one side is within weapon range of all units on the other side.

A3.) The effects of successive rounds on the target are independent.

A4.) Each unit has perfect knowledge of target locations and fires only at live target (one at a time) killing them at a constant rate, which does not depend on the number of targets alive.

A5.) Fire is uniformly distributed over surviving targets.

The above model implies a fight until one force is annihilated. Therefore the model will be slightly changed by introducing the concept of unit breakpoints, \( x_{bp} \) and \( y_{bp} \), which are simply force levels at which the side, who reaches it first "breaks off" the engagement, leaving the other side as a winner. Also, to be more precise, it should be noted that negative force levels for breakpoints equal zero or force levels
less than nonzero breakpoints are impossible. So the deterministic
LANCHESTER-type combat model with "square-law" attrition takes the
following form:

\[
\frac{dx}{dt} = \begin{cases} 
-ay & x_{bp} < X(t) \\
y_{bp} < Y(t) & 0 \\
0 & \text{otherwise}
\end{cases} \quad (2.8)
\]

\[
\frac{dy}{dt} = \begin{cases} 
-bx & x_{bp} < X(t) \\
y_{bp} < Y(t) & 0 \\
0 & \text{otherwise}
\end{cases} \quad (2.9)
\]

with initial conditions

\[
X(0) = x_0 \quad (2.10)
\]

\[
Y(0) = y_0 \quad (2.11)
\]

The model in this form, equations (2.8) through (2.11), was used for
comparisons throughout the thesis.

B. THE STOCHASTIC MODEL

There are several ways to include random variations in LANCHESTER-
type models. These are:

* The attrition rate coefficients may be random variables.
* The enemy's initial force level may be a random variable,
  weakening the assumption of perfect knowledge.
* The breakpoints may be random variables.
* The casualty rate is fixed, but the occurrence of casualties
  over time may be random.

The only random variation considered here will be the random occur-
rence of casualties over time. Another specification was to choose a
model similar to the "square-law" attrition in order to allow comparisons. In other words, the question to be asked is "how do random fluctuations in the occurrence of casualties modify the deterministic results of the square-law attrition process?"

The approach used here was a continuous parameter MARKOV chain model, where the time t varies continuously and the number of combatants on each side is a non-negative integer. Let $M(t)$ be the size of the X-force at time t with a particular state value $m$. Let $N(t)$ be the size of the Y-force at time t with a particular state value $n$. Let $m_0$ and $n_0$ be the initial force levels and $m_{bp}$, $n_{bp}$ be the breakpoint force levels of X and Y respectively. Fig. 1 shows the state space of this MARKOV chain model. Note that at a given time t, any state is described by the two force levels of the X and Y force. As each side loses units due to attrition and no replacements are allowed, it is easy to understand why BILLARD [1] referred to this type of process as a "bivariate death process."
Figure 1 - State Space of the Markov Chain Model
For the description of the stochastic square-law attrition process corresponding to the two deterministic differential equations (2.8) and (2.9), a system of many differential equations, depending on the battle termination model, is required. This system will be given for a fixed-force-level-breakpoint battle with square-law attrition.

The following assumptions yield the stochastic square-law attrition process.

A1.) The attrition process depends only on the current system state and time and not on the past history (this assumption is usually referred to as markovian property).

A2.) The probability \( P(\text{one } x \text{ casualty during the time interval } t \to t+h) = ah \)

A3.) The probability \( P(\text{one } y \text{ casualty during the time interval } t \to t+h) = bh \)

A4.) The probability of more than one casualty occurring in the time interval \( t \) to \( t+h \) is of the order of magnitude \( o(h) \), where \( \lim_{h \to 0} o(h)/h = 0 \).

A5.) No more casualties can occur once \( m = m_{bp} \) or \( n = n_{bp} \).

Making the time interval \( h \) infinitesimally small, the following set of forward CHAPMAN-KOLMOGOROV equations can be developed. Let \( P(t,m,n) \) be the probability that the system is in state \((m,n)\) at a time \( t \). For convenience each equation is related to a region in the state space shown in Fig. 2.
For $m = m_0$ and $n = n_0$, Region I

$$\frac{dP}{dt}(t, m_0, n_0) = -(a_{n_0} + b_{m_0}) P(t, m_0, n_0) \quad (2.12)$$

for $m_{bp} < m < m_0$ and $n = n_0$, Region II

$$\frac{dP}{dt}(t, m, n_0) = a_{n_0} P(t, m + 1, n_0) - (a_{n_0} + b_m) P(t, m, n_0) \quad (2.13)$$

for $n_{bp} < n < n_0$ and $m = m_0$, Region III

$$\frac{dP}{dt}(t, m, n_0) = b_{m_0} P(t, m_0, n + 1) - (a_n + b_{m_0}) P(t, m_0, n) \quad (2.14)$$

for $m_{bp} < m < m_0$ and $n_{bp} < n < n_0$, Region IV

$$\frac{dP}{dt}(t, m, n) = a_n P(t, m + 1, n) + b_m P(t, m, n + 1) - (a_n + b_m) P(t, m, n) \quad (2.15)$$

for $m = m_{bp}$ and $n_{bp} < n < n_0$, Region V

$$\frac{dP}{dt}(t, m_{bp}, n) = a_{n_{bp}} P(t, m_{bp} + 1, n) \quad (2.16)$$

for $n = n_{bp}$ and $m_{bp} < m < m_0$, Region VI

$$\frac{dP}{dt}(t, m, n_{bp}) = b_m P(t, m, n_{bp} + 1) \quad (2.17)$$

for $m = m_{bp}$ and $n = n_{bp}$, Region VII

$$P(t, m_{bp}, n_{bp}) = 0 \text{ for all } t \quad (2.18)$$

because of the definition of a breakpoint force level. The initial condition is

$$P(0, m_0, n_0) = 1.0 \quad (2.19)$$
Figure 2 - REGIONS IN THE STATE SPACE
As $P(t,m,n)$ is a joint probability distribution, the following must also be true

$$0 \leq P(t,m,n) \leq 1.0 \tag{2.20}$$

and

$$\sum_{m=m_{bp}}^{n_{0}} \sum_{n=n_{bp}}^{n_{0}} P(t,m,n) = 1.0 \tag{2.21}$$
III. SOLVING THE DIFFERENTIAL EQUATIONS

A. SOLUTIONS FOR THE DETERMINISTIC MODEL

Force levels as a function of time were already given in equations (2.5) and (2.6). It is relatively easy to obtain analytical solutions for such simple deterministic models as described before. On the other hand, it is necessary to point out that for models with any degree of operational realism, analytical methods for solving the differential equations are usually not available. Therefore, some numerical method with a digital computer is usually used. TAYLOR [10] has summarized in his Appendix C the most widely used numerical methods, a discussion of which seems unnecessary at this point.

B. SOLUTIONS TO THE STOCHASTIC MODEL

Even for this relatively simple stochastic model with fixed force level breakpoints, which are usually nonzero, a complete set of general analytical solutions for the differential equations (2.12) through (2.19) has not been found. On the other side, given some minor restrictions like a fight to the finish or equal attrition rate coefficients, solutions, or at least solution methods have been proposed which will be briefly discussed in the next section.

First, the method for getting the state probabilities used here will be described. Numerical solutions were obtained using the fourth-order RUNGE-KUTTA method, which is probably one of the best known finite difference approximations to ordinary differential equations (next to the
EULER-CAUCHY-method). To increase the accuracy of the overall solutions, analytical results for certain regions of the state space were substituted. These analytical solutions will be stated now. For region I, i.e. no casualties on either side, the solution to (2.12) is

\[ P(t, m_0, n_0) = \exp - \left( a n_0 + b m_0 \right)t \]  

(3.1)

which can be derived by the standard method used for this kind of differential equation. For the boundary cases, region II and III, i.e. one of the two sides has not yet had a casualty, TAYLOR [10] has given the analytical expression as

For \( m_{bp} < m < m_0 \) and \( n = n_0 \), Region II

\[ P(t, m, n_0) = \frac{1}{J!} \left\{ \frac{a n_0}{b(e^{bt} - 1)} \right\}^J \exp(-b m_0 + a n_0) t \]  

(3.2)

where \( J = m_0 - m \)

For \( n_{bp} < n < n_0 \) and \( m = m_0 \), Region III

\[ P(t, m_0, n) = \frac{1}{K!} \left\{ \frac{b m_0}{a(e^{at} - 1)} \right\}^K \exp(-b m_0 + a n_0) t \]  

(3.3)

where \( K = n_0 - n \).

These two equations (3.2) and (3.3) were obtained by recursively solving equations (2.12), (2.13) and (2.14) "from the top down."

C. OTHER ANALYTICAL SOLUTIONS

The solutions or solution methods for getting the state probabilities will only be stated for the square-law attribution process. Only two were used for the numerical work for this thesis.
Apparently, one of the "oldest" analytic solutions was given by BROWN [3] in 1955 for the general stochastic LANCHESTER-type combat model with time independent attrition rates. His approach and solution will be briefly outlined for square-law attrition. Consider a path from state \((m_0, n_0)\) to some state \((m,n)\). This path can be described as a sequence of \(J = (m_0 - m)\) zeros and \(K = (n_0 - n)\) ones, where a zero corresponds to an X casualty and a one to a Y casualty. Using the binary representation of a positive integer, one can define to each realization of a battle path an integer \(k\) given by

\[
k = d_k,1d_k,2\cdots d_k,J+K
\]

where \(d_k,r = 1\) if the \(r^{\text{th}}\) casualty along a battle path corresponding to \(k\) is a Y casualty and \(d_k,r = 0\) otherwise. Also let \(I_{J,K}\) be the set of all positive integers whose binary representation contains exactly \(K\) ones and \(J\) zeros.

Then

\[
m_{k,r} = m_0 - r + \sum_{j=1}^{r} d_{k,j}
\]

\[
n_{k,r} = n_0 - \sum_{j=1}^{r} d_{k,j}
\]

Then BROWN [3] has shown that
\[ P(t,m,n) = \frac{1}{2\pi} \sum_{k \in I} \int_{0}^{J+K-1} K_{k,r} \exp(-iu) \cdot \frac{\exp(-it) - \exp(-t1(m_k,r,n_k,r'))}{1(m_k,r,n_k,r) - iu} \, du \] , \quad (3.4)

where \( i = \sqrt{-1} \),

\[ 1(m,n) = an + bm , \]

\[ K_{k,r} = \frac{g_{k,r+1}}{1 - iu / 1(m_k,r,n_k,r)} \]

and

\[ g_{k,r+1} = d_{k,r+1} an_{k,r} + (1 - d_{k,r+1}) bm_{k,r} \]

There was no indication that nonzero breakpoints were excluded. A discussion of this solution follows in the next section.

About 14 years later, in 1969, CLARK [4] proposed another approach which TAYLOR [10] called a "hybrid analytical-numerical" method. The restriction is that the breakpoints have to be zero, i.e. it is a fight to the finish. Although proposed for a general time independent attrition function, this approach will be outlined for "square-law" attrition. Then according to CLARK [4] the state probabilities are given by
for $0 < m \leq m_0$ and $0 < n \leq n_0$

$$P(t, m, n) = \sum_{j=m}^{m_0} \sum_{k=n}^{n_0} C_{j,k}^{m,n} \cdot \exp(-(a(k+b)j)t), \quad (3.5)$$

for $0 < m \leq m_0$ and $n = 0$

$$P(t, m, 0) = C_{0,0}^{m,0} + \sum_{j=m}^{m_0} \sum_{k=0}^{n_0} C_{j,k}^{m,0} \cdot \exp(-(a(k+b)j)t), \quad (3.6)$$

for $m = 0$ and $0 < n \leq n_0$

$$P(t, 0, n) = C_{0,0}^{0,n} + \sum_{j=m}^{m_0} \sum_{k=0}^{n_0} C_{j,k}^{0,n} \cdot \exp(-(a(k+b)j)t), \quad (3.7)$$

and at last there is to remember that $P(t, 0, 0) = 0$ for all times $t$. The constants $C_{j,k}^{m,n}$ are determined by a system of partial difference equations.

For $0 < m \leq m_0$ and $0 < n \leq n_0$

$$C_{j,k}^{m,n} = \frac{a n C_{j,k}^{m+1,n} + b m C_{j,k}^{m,n+1}}{a(n-k)+b(m-j)}, \quad (3.8)$$
for $0 < m \leq m_0$ and $0 < n = k \leq n_0$

\[
C_{j,n} = \frac{a}{b(m-j)} C_{j,n}, \quad (3.9)
\]

for $0 < m = j \leq m_0$ and $0 < n < k \leq n_0$

\[
C_{m,k} = \frac{b(m-j)}{a(n-k)} C_{m,k}, \quad (3.10)
\]

for $0 < m \leq m_0$ and $0 < n = k \leq n_0$

but $(m, n) \neq (m_0, n_0)$

\[
C_{m,n} = -\sum_{j=m}^{m_0} \sum_{k=n+1}^{m_0} C_{j,k} - \sum_{j=m+1}^{m_0} C_{j,k} \quad (3.11)
\]

with $C_{m_0,n_0} = 1.0$. 

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Also for \(0 < m < j \leq m_0\) and \(0 < n < k \leq n_0\)

\[
c^m,0_{j,k} = \frac{b_m c^{m,1}_{j,k}}{a_k + b_j}, \quad (3.12)
\]

Similarly for \(0 = m < j \leq m_0\) and \(0 < n < k \leq n_0\)

\[
c^0,n_{j,k} = \frac{a_n c^{1,n}_{j,k}}{a_k + b_j}, \quad (3.13)
\]

Then for \(1 \leq m \leq m_0\)

\[
c^m,0_0 = - \sum_{j=m}^{m_0} \sum_{k=1}^{n_0} c^m,0_{j,k}, \quad (3.14)
\]

and finally for \(1 \leq n \leq n_0\)

\[
c^0,n_0 = - \sum_{j=1}^{m_0} \sum_{k=n}^{n_0} c^0,n_{j,k}. \quad (3.15)
\]

Though having the publishing date of 1979, the next approach was published in June 1980 by BILLARD [1]. She considered the LANCHESTER-type square-law attrition combat model as a pure death-process and applied SEVERO's [8] recursive theorem for solving differential equations. As before, only a fight to the finish has been considered.
The first step is to identify each point \((m,n)\) in the state space by a counting coordinate \(k\), where
\[
k = (m_0+1)(n_0+1)
- m(n_0+1) - n
\] (3.16)

Then
\[
P[t,m,n] = P[t,k]
\] (3.17)

and the differential equations (2.12) through (2.18) take on a slightly different form. As an example, (2.15) will be given by
\[
\frac{dP}{dt}(t,k) = a_n P[t,k-n_0-1]+b_m P[t,k-1]
- (a_n+b_m)P[t,k]
\] (3.18)

The whole set of differential equations was then expressed in matrix terms as
\[
\frac{dP}{dt}(t) = BP(t)
\] (3.19)

with a solution given as
\[
P(t) = Ce(t)
\] (3.20)

where \(e(t)\) is the \((m_0+1)(n_0+1)\times 1\) -vector with elements \(\exp(b_k t)\) with \(b_k\) being the \(k\)th diagonal element of the matrix \(B\). The matrix \(B\) can be partitioned into submatrices, whose \(m\)-coordinate is common, due to the ordering defined by the counting coordinate \(k\) (Equation 3.16).

Then
\[
B = (b_{uv}), \ u,v = 1,2,...,m_0+1
\]
where the submatrices $b_{uv}$ have the elements

$$b_{uv} = (b_{uv}(p,q)), \ p,q = 1,2...n_0+1.$$  

So the matrix $B$ has the elements

$$b_{uu}(p,p) = -a(n_0-p+1)-b(m_0-u+1)$$

for $u = 1,2...m_0$ and $p = 1,2...n_0$

$$b_{uu}(p,p-1) = b(m_0-u+1) \text{ for } u = 1,2...m_0+1 \quad p = 2,3...n_0+1$$

and

$$b_{u,u-1}(p,p) = a(n_0-p+1) \text{ for } u = 2,3...m_0+1 \quad p = 1,2...n_0+1.$$  

All other elements are zero.

Thus, the matrix $B$ has at most 3 nonzero entries per row or column. The matrix $C$ can be partitioned in the same way. Then using SEVERO's [8] theorem and the special form of the matrix $B$, only a part of the $C$-matrix needs to be determined. This part will be omitted here, but the final result will be given by

$$P(t,k) = \sum_{j=1}^{k} c(k,j) \cdot \exp(b_{jt}) \quad (3.21)$$

where $c(k,j)$ is the $(k,j)^{th}$ element of the solution matrix $C$.

The previous two approaches have required that the force level breakpoints be zero. Now, a result will be given whose restriction is that the attrition rate coefficients be equal, but nonzero breakpoints are allowed. For further reference it will be called the Equal-Attrition-Rate-Coefficient-Solution (EARCS).
Let $a = b = f$.

For $m_{bp} \leq m \leq m_0$ and $n_{bp} < n \leq n_0$

\[
P(t, m, n) = \frac{C(m, n)}{(m_0 + n_0 - m - n)!} \cdot \left(1 - e^{-ft}\right)^{m_0 + n_0 - m - n} \cdot \exp(-f(m+n)t) \quad (3.22)
\]

for $m = m_{bp}$ and $n_{bp} < n \leq n_0$

\[
P(t, m_{bp}, n) = \frac{f^n}{n!} \cdot \frac{C(m_{bp} + 1, n)}{(m_{bp} + 1 + n)!} \cdot \sum_{k=0}^{J} (-1)^k \binom{j}{k} \left\{1 - \exp\left(-ft(m_{bp} + 1 + n + k)\right)\right\} \quad (2.23)
\]

where $J = m_0 + n_0 - m_{bp} - 1 - n$

for $n = n_{bp}$ and $m_{bp} < m \leq m_0$

\[
P(t, m, n_{bp}) = \frac{f^m}{m!} \cdot \frac{C(m, n_{bp} + 1)}{(m + 1 + n_{bp} + 1)!} \cdot \sum_{j=0}^{K} (-1)^j \binom{k}{j} \left\{1 - \exp\left(-ft(m + 1 + n_{bp} + j)\right)\right\} \quad (3.24)
\]

where $K = m_0 + n_0 - m - n_{bp} - 1$.

The coefficients $C(m, n)$ satisfy for $m_{bp} < m < m_0$ and $n_{bp} < n < n_0$ the following partial difference equation

\[
C(m, n) = nC(m+1, n) + mC(m, n+1) \quad (3.25)
\]
with the boundary conditions
\[ C(m, n_0) = (n_0)^{m_0-m} \text{ for } m_{bp} < m \leq m_0 \]
and
\[ C(m_0, n) = (m_0)^{n_0-n} \text{ for } n_{bp} < n \leq n_0 \]

This result has been developed using a method verbally proposed by TAYLOR. The method will now be outlined. ISBELL and MARLOW [6] described a stochastic LANCHESTER-type attrition process with a different attrition function. Instead of the attrition of one force being proportional to the number of enemies of the opposing force as in the square-law attrition (e.g. for the attrition of the M-force let
\[ A(m, n) = an \]
be the attrition rate and
\[ B(m, n) = bm \]
the attrition rate for the N-force with square-law attrition), their attrition rates looked like
\[ A(m, n) = an+cm \]
and
\[ B(m, n) = bm+dn \]
with the restriction that
\[ a+c = b+d. \]
But with \( c=d=0 \) and \( a=b=f \) we are back to square-law attrition. This leads to equations (3.22) and (3.25). Equations (3.23) and (3.24) were derived in the following way (e.g. for 3.23). Solving equation (3.22) for \( m = m_{bp}+1 \) yields
\[ p(t, m_{bp}, n) = \frac{C(m_{bp}+1,n)}{(m_0+n_0-m_{bp}-1-n)!} \cdot \exp(-ft(m_{bp}+n)) \]
\[ \cdot (1-e^{-ft})^{m_0+n_0-m_{bp}-1-n} \]  

substituting for the second factor its BINOMIAL expansion
\[ (1-e^{-ft})^J = \sum_{k=0}^{J} (-1)^k \binom{J}{k} e^{-ftk}(1)^{J-k} \]
with \( J = m_0+n_0-m_{bp}-1 \) and multiplying through by the third factor. Then using equation (2.16), the differential equation for \( m = m_{bp} \) and \( n_{bp} < n_n \), and substituting equation (3.26) into the extended form, it can now easily be integrated to yield equation (3.23).

D. DISCUSSION

In the discussion of the analytical solutions outlined in the last section, there is one important point. BROWN [3] himself points out that unless \( m \) is close to \( m_0 \) and \( n \) is close to \( n_0 \), his result (equation (3.4)) is of "little practical interest." Most of the analytical solutions, especially for more general LANCHESTER-type models, have little more than "symbolic" character. BROWN's solution is a good example of that.

In comparing the solutions given by BILLARD [2] and CLARK [4], this author has the feeling that both solutions are equivalent and only the representation is different. This
intuitive guess needs verification. It may be concidence that CLARK [4] and SEVERO [8] published their work in the same year.

The last presented solution (equation (3.22) through (3.24)) seems to be relatively handy for use on a computer. It has a big advantage over numerical solution methods other than its accuracy, because it is an exact result. Like CLARK's method, the coefficients have to be calculated only once for a given set of input data. Then, to get the state probabilities for a certain point in time you have to make only one set of calculations, as opposed to the numerical methods where one has to go from time $t = 0$ to time $t = t$ in small time steps and then have only an approximate result.

E. IMPORTANCE OF THE STATE PROBABILITIES

The state probabilities as a function of time are the key to calculating several quantities of interest. These are expected force levels as a function of time, variances and standard deviations in the force levels and also the probability of winning. These quantities are necessary to legitimately compare the stochastic with the deterministic results.

To get at least a feeling of how the state probabilities evolve over time, the joint probability distribution will be presented in a 3-D-picture. It is indeed surprising that more use has not been made of computer graphics to
investigate the dynamics of a stochastic LANCHESTER-type combat model. Table 1 gives the data used for the next five figures. These figures may be thought of as "snapshots" of the joint probability for the survivors in this battle taken at a sequence of increasing times.


**TABLE 1**

Data for the Numerical Example

<table>
<thead>
<tr>
<th>Force Levels</th>
<th>( m_0 = 40 )</th>
<th>( m_{bp} = 0 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n_0 = 40 )</td>
<td>( n_{bp} = 0 )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attrition Rates</th>
<th>( a = 0.008 ) M casualties per minute and N firer</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b = 0.004 ) N casualties per minute and M firer</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>At Times</th>
<th>( t_1 = 0.025 \ t_f )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_2 = 0.250 \ t_f )</td>
<td></td>
</tr>
<tr>
<td>( t_3 = 0.500 \ t_f )</td>
<td></td>
</tr>
<tr>
<td>( t_4 = 0.750 \ t_f )</td>
<td></td>
</tr>
<tr>
<td>( t_5 = 1.000 \ t_f )</td>
<td></td>
</tr>
</tbody>
</table>

where \( t_f = 155.81 \) minutes is the time a deterministic battle with the same force levels and unit breakpoints ends, i.e. \( x(t_f) = 0.0 \) and \( y(t_f) = 28.28 \)
Figure 3 - PLOT OF JOINT PROBABILITIES $P(t,m,n)$ with data according to Table 1
Figure 4 - Plot of joint probabilities $P(t,m,n)$ with data according to Table 1
Figure 5 - PLOT OF JOINT PROBABILITIES $P(t,m,n)$

with data according to Table 1
Figure 6 - Plot of joint probabilities $P(t, m, n)$ with data according to Table 1
Figure 7 - Plot of joint probabilities $P(t,m,n)$

with data according to Table 1
At the time $t = 0$ all probability is located at $(m_0, n_0)$ in the state space (Region I). As time passes, the probability mass is distributed over more states, with the mode moving away from the diagonal towards the winning side. All points in the state space with breakpoints, i.e. $(m_{bp}, n)$ and $(m, n_{bp})$ for all $m$ and $n$, are absorbing states; probability mass is absorbed in those states. The sum of probability mass in Region V (see Fig. 2) represents the probability, that the N-force wins at that given time, in Region VI that the M-force wins.

The next five figures show a similar sequence of plots for the joint probability $P(t, m, n)$ for the force levels $M(t)$ and $N(t)$. The data is explained in Table 2. Note the small differences because of the nonzero force level breakpoints. Probability mass having reached the breakpoint "piles" up there. The state space is reduced by the fixed force level breakpoints, but the probability distribution evolves basically in the same qualitative manner as in the previous example.
TABLE 2

Data for the Numerical Example 2

<table>
<thead>
<tr>
<th>Force Levels</th>
<th>Force Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_0 = 40$</td>
<td>$m_{bp} = 8$</td>
</tr>
<tr>
<td>$n_0 = 40$</td>
<td>$n_{bp} = 8$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Attrition Rates</th>
<th>Attrition Rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a = 0.008$</td>
<td>$M$ casualties per minute and $N$ firer</td>
</tr>
<tr>
<td>$b = 0.004$</td>
<td>$N$ casualties per minute and $M$ firer</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>At Times</th>
<th>At Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_1 = 0.025 , t_f$</td>
<td>$t_1 = 0.025 , t_f$</td>
</tr>
<tr>
<td>$t_2 = 0.250 , t_f$</td>
<td>$t_2 = 0.250 , t_f$</td>
</tr>
<tr>
<td>$t_3 = 0.500 , t_f$</td>
<td>$t_3 = 0.500 , t_f$</td>
</tr>
<tr>
<td>$t_4 = 0.750 , t_f$</td>
<td>$t_4 = 0.750 , t_f$</td>
</tr>
<tr>
<td>$t_5 = 1.000 , t_f$</td>
<td>$t_5 = 1.000 , t_f$</td>
</tr>
</tbody>
</table>

where $t_f = 120.68$ minutes is the time a deterministic battle with the same force levels and unit breakpoints ends, i.e. $x(t_f) = 8.0$ and $y(t_f) = 28.83$
Figure 8 - PLOT OF JOINT PROBABILITIES $P(t,m,n)$

with data according to Table 2
Figure 9 - PLOT OF JOINT PROBABILITIES $P(t, m, n)$
with data according to Table 2
figure 10 - PLOT OF JOINT PROBABILITIES $P(t, m, n)$

with data according to table 2
Figure 11 - PLOT OF JOINT PROBABILITIES $p(t,m,n)$

with data according to Table 2
Figure 12 - PLOT OF JOINT PROBABILITIES $P(t, m, n)$

with data according to Table 2

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IV. EVOLUTION OF THE FORCE LEVELS

A. THE DETERMINISTIC MODEL

The evolution of force levels as a function of time, X(t) and Y(t), has already been stated in equations (2.5) and (2.6). The next two figures show the force levels with different breakpoints. It is easy to realize that introducing a nonzero breakpoint does not change the underlying function. In other words, using X(t) as an example, for both figures the same curve was used but at the point where the X-force reaches its breakpoint, the curve is "cut." From that point in time, there are no more changes in the force levels. So introducing a nonzero breakpoint only shifts the discontinuity (marked by DX1 in Fig. 13) up along the curve to DX2.

The probability for one side to win is either one or zero, because it is a deterministic model. To easily determine which side is going to win, a victory prediction condition can be obtained by solving each force level equation (2.5) and (2.6) for the time to reach its breakpoint \( t_{xbp} \) by substituting \( X(t)=x_{bp} \) and \( t_{ybp} \) by substituting \( Y(t)=y_{bp} \). Then \( X \) will win if \( t_{ybp} < t_{xbp} \), which leads to the prediction condition. \( X \) will win a fixed force breakpoint battle if and only if

\[
x_0/y_0 > \frac{a(y_0^2 - y_{bp}^2)}{b(x_0^2 - x_{bp}^2)} \quad (4.1)
\]

This shows that given the initial data one can predict the outcome of the battle in terms of force levels and time until the battle finishes.
Figure 13 - FORCE LEVELS OVER TIME

Deterministic model with Breakpoint $x_{bp} = 0$
Figure 14 - FORCE LEVELS OVER TIME

Deterministic Model with Breakpoint $x_{bp} > 0$
B. THE STOCHASTIC MODEL

Every possible state \((m,n)\) in the state space has associated with it a certain probability between zero and one which is a function of time. In order to gain more insight into the stochastic process not a single realization of a battle has to be considered, but an average battle. Therefore the expected value of the force levels (i.e. averages) as a function of time and the variances in the force levels were investigated.

The straightforward way to compute the expected force levels involves the knowledge of the probability distribution \(P(t,m,n)\). Then

\[
E(M(t)) = \sum_{m_n} P(t,m,n) \quad \text{(4.2)}
\]

\[
E(N(t)) = \sum_{n_m} P(t,m,n) \quad \text{(4.3)}
\]

are the expected values of the force levels as a function of time.

There are some other ways to calculate the expected force levels, one of which will be stated here. Recall the "hybrid-analytical-numerical" method to get the state probabilities (equations 3.5 through 3.15). CLARK [4] has also shown that the \(i\)th moment of, for example, the \(M\)-force level may be computed as

\[
E(M^i(t)) = D_{0,0}^{(i)} + \sum_{j=1}^{m_0} \sum_{k=1}^{n_0} D_{j,k}^{(i)} \exp(-(ak+bj)t) \quad \text{(4.4)}
\]

with for \(1 \leq j \leq m_0\) and \(1 \leq k \leq n_0\)
\[
D_{j,k}^{(i)} = \sum_{m=1}^{j} m^i \sum_{n=0}^{k} c_{j,k}^{m,n}, \quad (4.5)
\]

\[
D_{0,0}^{(i)} = \sum_{m=1}^{m_0} m^i c_{0,0}^{0,n}, \quad (4.6)
\]

This again emphasizes the strong point of CLARK's solution. For a given set of battle parameters the coefficients \(c_{j,k}^{m,n}\) have to be computed only once. Then with this information and relatively small computational effort not only the state probabilities but also the first and second moment of the force levels can be computed. This determines the variance in the force levels at the same time, e.g.

\[
\text{Var}(M(t)) = E(M^2(t)) - E(M(t)) \cdot E(M(t)). \quad (4.7)
\]

On the other side, the weak point is that CLARK [4] considered only breakpoints equal zero.

Many authors have discussed one side's probability of winning or probability of winning conditioned on a certain number of survivors, which always eliminated the parameter time by integrating from time \(t=0\) to infinity. This may be legitimate to answer absolute (meaning time independent) questions about who will win, but for direct comparisons with the deterministic model, this author has the feeling that the best question to ask regarding a winner is:

What is the probability of one side winning given the stochastic battle lasted as long as the deterministic one?

The calculation of these probabilities gives another interesting probability, because given the time \(t = t_f\) (final time of the deterministic battle)
\[ P(\text{battle has not yet finished}) = 1 - P(M \text{ wins}|t=t_f) - P(N \text{ wins}|t=t_f) \quad \text{(4.8)} \]

There has also been work done regarding the distribution of the time to finish a battle. But this is beyond the scope of this thesis (SPRINGALL [9]).

C. DIFFERENCES IN THE FORCE LEVELS

The deterministic model, especially the force level equations (2.5) and (2.6), describe a process with continuous state parameters where, in reality, the possible states are integers. Quoting from LANCHESTER [7]:

Since the forces actually consist of a finite number of finite units (instead of an infinite number of infinitesimal units) the end of the curve must show discontinuity, and break off abruptly when the last man is reached; the law based on averages evidently does not hold rigidly when the numbers become small.

LANCHESTER suggested that his differential equations may be good approximations only as long as the force sizes are large. He also stated that the equations are based on averages, implying an underlying stochastic process.

This shows that there must be a difference in the force levels which should become significant when the number of combatants is small. This difference was called bias by CLARK [4] and TAYLOR [10]. It can be shown that

\[ \frac{dE(M(t))}{dt} = -aE(N(t)) + bB_n(t) \quad \text{(4.9)} \]

and

\[ \frac{dE(N(t))}{dt} = -bE(M(t)) + bB_m(t) \quad \text{(4.10)} \]

where
\[ B_n(t) = n_{bp} \sum_{m_{bp} + 1}^{m_0} P(t, m_{bp}, n_{bp}) + \sum_{n_{bp} + 1}^{n_0} nP(t, m_{bp}, n) \quad (4.11) \]

and

\[ B_m(t) = m_{bp} \sum_{n_{bp} + 1}^{n_0} P(t, m_{bp}, n) + \sum_{m_{bp} + 1}^{m_0} mP(t, m_{bp}, n). \quad (4.12) \]

The bias terms \( B_m(t) \) and \( B_n(t) \) can be interpreted as the expected values of \( M(t) \) or \( N(t) \) conditioned on the fact that the battle has already ended at time \( t \), for example,

\[ B_m(t) = E(M(t) | N(t) = n_{bp} \text{ or } M(t) = m_{bp}) \quad (4.13) \]

In other words, equation (4.9) says the expected casualty rate of the M-force is proportional to the expected number of survivors of the N-force given neither of the two forces has reached its breakpoint.

Define the bias of the X-force as \( \Delta x(t) = E(M(t)) - X(t) \) and the bias of the Y-force as \( \Delta y(t) = E(N(t)) - Y(t) \). Then using equations (2.8) and (2.9) together with (4.9) and (4.10) it follows that

\[ \frac{d}{dt} \Delta x = -a\Delta y + aB_n(t) \quad (4.14) \]

\[ \frac{d}{dt} \Delta y = -b\Delta x + bB_m(t) \quad (4.15) \]

with the initial conditions \( x(0) = 0 \) and \( Y(0) = 0 \). This has the solution

\[ \Delta x(t) = \sqrt{ab} \int_{0}^{t} \left\{ B_n(s) \sqrt{a/b \cosh(\sqrt{ab}(t-s))} - B_m(s) \sinh(\sqrt{ab}(t-s)) \right\} ds, \quad (4.16) \]
and

\[
\Delta y(t) = \gamma_{ab} \int_0^t \left( B_m(s) \sqrt{b/a} \cosh(\sqrt{ab}(t-s)) - B_n(s) \sinh(\sqrt{ab}(t-s)) \right) ds. \tag{4.17}
\]

Since for a fixed, nonegative argument \( z \), the \( \cosh(z) \) is always greater than the \( \sinh(z) \), it is easy to visualize that in most of the cases both biases are positive, meaning the expected force levels of the stochastic model are higher than the deterministic force levels. This has been shown by CLARK [4] and CRAIG [5] and confirmed by this author. In the rest of the cases the winner's bias is negative or close to zero and the loser's bias is positive. Two examples are given in Table 3.
TABLE 3

Examples for cases where one bias is positive and the other bias is negative.

A. Y-force wins in a fight to the finish

\[ x_0 = y_0 = 40 \quad a = 0.08 \]

\[ x_{bp} = 0 \quad b = 0.04 \]

\[ y_{bp} = 0 \]

\[ t_f = 15.581 \quad \Delta x(t_f) = 3.22 \]

\[ \Delta y(t_f) = -0.23 \]

B. Y-force wins in a fight with equal initial force levels, but different breakpoints.

\[ x_0 = y_0 = 15 \quad a = 0.08 \]

\[ x_{bp} = 12 \quad b = 0.08 \]

\[ y_{bp} = 6 \]

\[ t_f = 2.85 \quad \Delta x(t_f) = 0.15 \]

\[ \Delta y(t_f) = -0.10 \]
An interesting point has to be mentioned regarding case B of Table 3. Here the expected force level of the winner is smaller than the expected force level of the loser at the time a deterministic battle ends.

To get a better feeling for the differences in the force levels, the next two figures show as an example a large spectrum of force level behavior. The data and notation is described in Table 4. There are four battles with four different breakpoints drawn as they evolve over time from zero to the time an equivalent deterministic battle ends.
TABLE 4

\[ X_0 = 40 \quad X_{bp}(i) = 40 - 0.2i \]
\[ Y_0 = 40 \quad Y_{bp}(i) = 40 - 0.2i \]
\[ a = 0.09 \quad \text{for } i = 1, 2, 3, 4 \]
\[ b = 0.07 \]
\[ M_i = E M(t) \quad \text{for } i = 1, 2, 3, 4 \]
\[ N_i = E N(t) \]

Where the index \( i \) corresponds to the battle with the \( i \)th breakpoint force level:

- \( X \)-force is always loser
- \( Y \)-force is always winner
Figure 15 - DETERMINISTIC AND EXPECTED FORCE LEVELS FOR
THE X - FORCE

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Figure 16 - Deterministic and Expected Force Levels for the Y-Force
CRAIG [5] has formulated hypotheses concerning the biases in the average force levels based on his work. His hypotheses were partially confirmed, but in some cases they have to be modified. Therefore, another similar set of hypotheses will be given and supported by Fig. 15 and Fig. 16, as well as some of the later figures.

H 1) Given fixed initial force levels and attrition rate coefficients, as the breakpoint force levels increase, the numerical bias for the loser decreases. The biases for the winner do not show this monotone trend except for the case of symmetric parity.

H 2) Everything else constant, the bias of the loser increases with increasing initial force levels; this is also true in the symmetric parity case for both forces.

H 3) Given the initial force level ratio is close to one at the time corresponding to the end of the deterministic battle, the bias of the loser is always larger than the bias of the winner.

H 4) At the time corresponding to the end of a deterministic battle, the biases become larger as the forces come closer to parity.

H 5) The biases at times corresponding to less than one half the duration of the deterministic battle are negligible.

The case of symmetric parity, i.e. equal initial force levels, breakpoints and equal attrition rate coefficients seems to be kind of a "limiting" case. For example, at parity the biases of both forces behave in the same manner and are equal. In Fig. 17 the biases at the time a deterministic battle ends as a function of the initial force levels and as a function of the breakpoints are presented. It is also another verification for the hypotheses H 1 and H 2.
Figure 17 - BIASES IN SYMMETRIC PARITY
Figure 18 - BIASES WITH DIFFERENT INITIAL FORCE LEVELS

$\Delta x = \Delta y$

Case I $\gamma_0 = 10$
II $\gamma_0 = 11$
III $\gamma_0 = 12$

$\chi_0 = 10 \quad f = 0.08$
Figure 19 - Biases with Different Attrition Rate Coefficients

\[ x_0 = y_0 = 40 \]
\[ x_{BP} = y_{BP} \]

Case I \( a = b = 0.08 \)

Case II \( a = 0.09 \)
\( b = 0.07 \)

Case III \( a = 0.08 \)
\( b = 0.04 \)
Considering the changes in magnitude of the biases for battles like in Fig. 15, 16 and 17, CRAIG [5] came to the conclusion that when the forces are closer to parity, the biases at the deterministic battle's end increase. Several battles were fought starting with symmetric parity and then varying the force levels and the attrition rate coefficients. Sample results are shown in Fig. 18 and Fig. 19. In Fig. 18, the initial force levels were changed giving the Y-force ten and twenty percent higher initial force levels. The biases at the end of the deterministic battle are plotted as a function of the breakpoint force level ratio \( r = \frac{x_{bp}}{x_0} \).

Fig. 18 supports CRAIG's hypothesis, as does Fig. 19. Here not the initial force levels but the attrition rate coefficients were changed in order to deviate from symmetric parity. The last way to deviate from symmetric parity is a case where the deterministic model gives equal answers for different battles. The data and the results are shown in Table 5.
TABLE 5

Equal initial force level battle with non equal breakpoints

\[ x_0 = 15 \quad y_0 = 15 \quad a = b = f = 0.08 \]

<table>
<thead>
<tr>
<th>( x_{bp} )</th>
<th>( y_{bp} )</th>
<th>( \Delta x(t_f) )</th>
<th>( \Delta y(t_f) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>12</td>
<td>1.08</td>
<td>1.08</td>
</tr>
<tr>
<td>12</td>
<td>9</td>
<td>0.71</td>
<td>0.63</td>
</tr>
<tr>
<td>12</td>
<td>6</td>
<td>0.15</td>
<td>-0.10</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>0.68</td>
<td>0.58</td>
</tr>
<tr>
<td>9</td>
<td>9</td>
<td>1.62</td>
<td>1.62</td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>1.14</td>
<td>0.93</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>1.06</td>
<td>0.75</td>
</tr>
<tr>
<td>6</td>
<td>6</td>
<td>2.15</td>
<td>2.15</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>1.67</td>
<td>1.22</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>2.84</td>
<td>2.84</td>
</tr>
</tbody>
</table>
The X-force level at time $t_f$ is the same as the Y-force level. Thus, the expected force level for the winner (i.e. the Y-force) is smaller than the expected force level of the loser (the X-force), because $\Delta x(t_f)$ is always larger than $\Delta y(t_f)$. This is easy to see when one remembers the way the expected force level is computed (equation (4.3)). Since the Y-force has a lower breakpoint, there are states $(m,n)$ possible where $n_{bp} < n < m_{bp}$. Apparently these states have a nonzero probability associated with them, which decreases the expected force level below the expected value for the X-force. This might be a starting point for further studies.

D. VARIABILITY IN THE FORCE LEVELS

Naturally in the deterministic case there does not exist any variability in the force levels. On the other hand, for the stochastic model, the variance in the force levels as a function of time is a measure of the dispersion of the number of survivors about their mean value.

CLARK [4] has hypothesized two different types of behavior for the variance in the force levels, which are shown in Fig. 20 for the data presented in Table 2. The first type of behavior is that of the variance for the N-force, i.e. the variance increases monotonely as a function of time and is asymptotic to a limiting value. It was found that this type of behavior occurs when the side is going to win and for the case of symmetric parity. The second type of behavior shown is the variance of the M-force, $\text{Var}(M(t))$, as a function of time. This increases to a maximum value then decreases asymptotically to a limiting value. This type of behavior is associated with the loser of the battle.
The variance in the force levels is a function of the initial and breakpoint force levels, the battle time and the attrition rate coefficients. Unfortunately one does not know what this dependence is. Based on many numerical results a set of hypotheses will be stated and the next figures will support them.

H 1) Given fixed initial force levels and attrition rate coefficients, as the breakpoint force levels increase the variance of the force levels decrease.

H 2) Everything else constant the variance of the loser's force level increases with increasing initial force levels. This is also true for both variances in the case of symmetric parity.

H 3) Given the initial force ratio is close to one at the time corresponding to the end of the deterministic battle the variance of the loser's force level is always smaller than the winner's variance.

H 4) At the time corresponding to the end of the deterministic battle the variance in the loser's force level increases as the forces come closer to parity. This trend is not true for the variance of the winner, except for the case of symmetric parity.

It was the intention of this author that the set of cases to illustrate the hypotheses are the same as in the illustrations (Fig. 17, 18 and 19) of the hypotheses about biases. So, Fig. 21 shows the force level variances for the different initial force levels and different breakpoints for the case of symmetric parity. In Fig. 22 the variances for a battle with equal attrition rate coefficients but varying initial force levels show that H 4 is only true for the loser. This point is emphasized by Fig. 23, where with constant and equal initial force levels the attrition rate coefficients were varied.
Figure 20 - FORCE LEVEL VARIANCES OVER TIME
Figure 21 - VARIANCES IN SYMMETRIC PARITY

\[ r = \frac{X_{BP}}{X_0} \]
$X_0 = 10 \ f = 0.08$

Case I $\gamma_0 = 10$

II $\gamma_0 = 11$

III $\gamma_0 = 12$

Figure 22 - VARIANCES WITH DIFFERENT INITIAL FORCE LEVELS
$r = \frac{x_B}{x_0}$

$X_0 = Y_0 = 4.0$

$X_B = Y_B$

Case I: $a = b = 0.08$

Case II: $a = 0.09$

Case III: $a = 0.08$

$b = 0.04$

Figure 23 - Variances with different attrition rate coefficients
V. COMPUTATIONAL ASPECTS

A. USING THE NUMERICAL SOLUTION

For most of the numerical work, the state probabilities have been obtained using the fourth-order RUNGE-KUTTA method. The accuracy of the results was increased by substituting the available analytical results for the Regions I, II and III.

The disadvantage is that this solution method needs a lot of CPU-time. For the battle in Example 1, with the data given in Table 1, the calculation of the state probabilities, expected force levels and variances led to a CPU-time on an IBM-360 computer of almost 90 minutes with a time step size of 0.05 minutes. That was the reason why, in the examples the attrition rate coefficients were increased by one magnitude, which brought the computer usage down to a CPU-time of around 12 minutes with the same time step size of 0.05 minutes. The sum of the state probabilities at every time step was used as a measure of accuracy. Surprisingly, its deviation from 1.0 was always in the fourth or fifth decimal, which proves the robustness of the RUNGE-KUTTA method. Also, the fact that for the Regions I, II and III analytical solutions were substituted at each time step did not change the final outcome considerably. It was found that without the analytical partial solutions the sum of probabilities tended to be slightly higher, changing the sum of probabilities from, for example, 0.99998 to 1.00003.
B. THE EQUAL ATTRITION RATE COEFFICIENT SOLUTION

After the development of the equal attrition rate coefficient solution (EARCS) outlined in Ch. III.C, it was implemented on an IBM-360 computer. The CPU-time for the calculation of the state probabilities, expected force levels and variances for a given point in time always stayed below 20 seconds, which emphasizes its computational advantage.

Further research showed two shortcomings of the EARCS, which are easily overlooked. The coefficients $C(m,n)$ vary over a wide range starting at 1.0 and depending on the initial force levels. For example for a battle with

$m_0 = 20 \quad m_{bp} = 15$
$n_0 = 40 \quad n_{bp} = 20$
$f = 0.08 \quad t_f = 1.60995$

$C(20,40) = 1.0 \quad$ but $\quad C(16,21) = 4.9297077276 \times 10^{33}$

Also, the binomial coefficients in equations (3.23) and 3.24) vary over a wide range starting at 1.0 to 1352078 for the above example. This shows that the capacity the computer, in terms of the number of significant digits, is able to carry limits the implementation of this solution in the present form.

Another reason why this solution is not the end of the numerical problems is the fact that in the given form, equations (3.23) and (3.24) require computation of an alternate sum consisting of terms whose factors are relatively large binomial coefficients and small numbers between zero and one. This produces truncation errors, which yield nonsensical results like negative variances and sums of probabilities greater than one.
VI. CONCLUSIONS

Throughout this thesis, only LANCHESTER-type square-law attrition with fixed initial force levels and fixed attrition rate coefficients has been considered for a deterministic and a stochastic version. The stochastic version required much more computational effort. So, given the need for an analytical model as opposed to the use of simulation, there is not much to gain from the application of a stochastic model when the force levels are large and the forces are not near parity. In these cases the deterministic version essentially produces the same results, at least in qualitative terms. For smaller force levels or forces near parity, the stochastic version may be helpful to get more information about the dynamics of combat.

Also, there exist one case where the deterministic version cannot differentiate between several different battles. That is the case of equal initial forces, equal attrition rate coefficients, but different breakpoint force levels. This also rectifies the further development of the equal-attrition-rate-coefficient-solution (EARCS).

Using an analytical model, the discussed way of introducing randomness into the model seems not to be very enlightening. Therefore, it is suggested that another way to include random effects should be explored. The author's opinion is that working with attrition rate coefficients which are random variables seems more promising to gain insight into the dynamics of combat. Further down the line there should be some
consideration on the usage of combinations of the possibilities to include random effects as given in Chapter II.B.
APPENDIX A

THIS PROGRAM COMPUTES THE STATE PROBABILITIES USING THE FOURTH ORDER RUNGE-KUTTA METHOD. PLOTS OF THE EXPECTED FORCE LEVELS AND VARIANCES AS WELL AS 3-D-PLOTS FOR THE STATE PROBABILITIES ARE OBTAINED.

DIMENSION P1(33,33), P2(33,33), T3D(20)
DIMENSION XMT(500), XNT(500), VM(500), VN(500),
       VNB(551), VMB(551), VQ(551), VARX(551), VARY(551), TIM(551)
DIMENSION EST(313), D(313), F(12), SIZE(2), KX(100), KT(100), WK(41,41,9)
DIMENSION PC(41,41), CST(41), CETERM(41)
LOGICAL IDN(41,41)
DIMENSION DETERM(313)
REAL TIL(12)/12=
REAL K1, K2, K3, K4
CALL ERRSET(208,600.,-1,1)
F(1)=0.
F(2)=0.
LINES=0
SIZE(1)=6.
SIZE(2)=8.
QFLAG = 0.
NKXT=100
READ(5,21) MBP, MO, NBP, NO
READ(5,22) AA, BB
READ(5,22) H, FTIM
READ(5,21) N3D
READ(5,22) EPSQ, EPSPTT
T3D(I)= 9999.
IF (N3D .LT. 1) GO TO 25
READ(5,22) (T3D(I), I=1,N3D)
CONTINUE
N3D=NUMBER OF 3D-PLOTS, H=SIZE OF TIME STEP
FTIME=FINAL TIME, EPSQ, EPSPTT ARE ZERO LEVELS
T3D(I)= FRACTION OF FTIM WHEN TO PLOT 3D
DO 10 I=1,N3D
T3D(I)=FTIM=T3D(I)
10 CONTINUE
FORMAT(16I5)
FORMAT(8F10.5)
WRITE(6,28) MBP, MO, NBP, NO
WRITE(6,29) AA, BB
WRITE(6,30) H, FTIM
WRITE(6,31) N3D
WRITE(6,32) 'INITIAL H & FINAL TIME (= LOOPS = H)', 5X, 2F10.3/
WRITE(6,33) N3D
WRITE(6,34) 'OF 3-D PLOTS', 2X, 16
IF (N3D .LT. 1) GO TO 98
WRITE(8,24) EPSO, EPSPTT
24 FORMAT(/ 5X,'EPSO=',F10.5,5X,'EPSPTT=',F10.5)
WRITE(6,32) (T30(I), I=1,N30)
32 FORMAT(/ 5X, 'AT TIME', 2X, 10F10.3 /)
36 CONTINUE
37 MO = MO + 1
38 NO = NO + 1
39 MS = MO - NBP
40 MSL = MS + 1
41 NSL = NS + 1
42 BMD = BB * NO
43 AND = AA * NO
44 QANB = RAND / BB
45 QBMN = BMD / AA
46 BAT = -(BMD + AND)
47 DO 47 M1 = 1, MS
48 VM(M1) = MBP * M1 - 1
49 CONTINUE
50 TIME = M
51 N3 = 1
52 TPLT = T3D(N3)
53 TIME = 0.
54 IF (TIME .GT. FTIME) GO TO 210
55 CONTINUE
56 TIME = M = L
57 L = L + 1
58 LB = 0
59 TMLM(L) = TIME
60 IF (L .EQ. 2) GO TO 53
61 IF (TIME .LT. TPLT) GO TO 60
62 C
63 C SET NEXT PLOT TIME
64 C
65 N3 = N3 + 1
66 TPLT = T3D(N3)
67 IF(N3.GT.N3D) TPLT=9999.
68 CONTINUE
69 C
70 C LB = L WHEN TIME TO PLOT
71 C
72 LB = L
73 EBT = EXP(BB = TIME) - 1.
74 EAT = EXP(AR = TIME) - 1.
75 AE = QANB = EBT
76 BE = QBMN = EAT
301 ORE - TORT TIME
102 FJ = 1.
103 JJ = 1
104 C
105 C NO VALUE OF J = ZERO AT NO, NO
106 C
107 FK = 1.
108 KK = 1
109 QFK = 1.
110 QFJ = 1.
111 C
112 C NO VALUE OF K = ZERO AT NO, NO
113 C
114 GO CONTINUE
115 IF (L .EQ. 1) GO TO 500
116 QQ = 0.
117 DO 400 NI = 1, NS
118 N = NO1 - NI
119 NL = NSL - NI
120 NI = NL + 1
121 ANJ = RA = N
122 C
123 C
124 DO 300 MI = 1, MS
125 M = MO1 - MI
126 ML = MSL - MI
127 MLI = ML + 1
128 BMI = BB = M
129 ABA = ANJ + BMI
130 IF (M .EQ. NO) GO TO 502
131 IF (M .EQ. NBP) GO TO 504
132 IF (N .EQ. NO) GO TO 506
133 IF (N .EQ. NBP) GO TO 507
134 C
135 C DEFAULTS TO ALL INSIDE POINTS
136 C
137 K1 = ANJ*PI2 (ML1, NL) + BMI*PI2 (ML, NL) - ABA*PI2 (ML, NL)
138 PT = ANJ*0.5 + PI (ML1, NL) + PI2 (ML, NL) + BMI*0.5 + PI (ML, NL)
139 PT2 (ML, NL)
140 K2 = PT = ABA = (PI2 (ML, NL) + H*0.5*K1)
141 K3 = PT = ABA = (PI2 (ML, NL) + H*0.5*K2)
142 K4 = ANJ*PI1 (ML1, NL) + BMI*PI1 (ML, NL) - ABA*PI1 (ML, NL) + H*K3
143 PI (ML, NL) = P2 (ML, NL) + (H/6.0) = (K1 + 2.0*K2 + 2.0*K3 + K4)
144 GO TO 200
145 502 IF (N .EQ. NO) GO TO 503
146 IF (N .EQ. NBP) GO TO 507
147 C
148 C M = NO, N = NO, NBP
149 C
150 K1 = BMI*PI2 (ML, NL) - ABA*PI2 (ML, NL)

75
151 \( PT = BM1=0.5 \times (P1(ML,NI) + P2(ML,NI)) \)
152 \( K2 = PT - ABA \times (P2(ML,NI) + H*K1=0.5) \)
153 \( K3 = PT - ABA \times (P2(ML,NI) + H*K2=0.5) \)
154 \( K4 = BM1 = P1(ML,NI) - ABA \times (P2(ML,NI) + H*K3) \)
155 \( P1(ML,NI) = P2(ML,NI) + (H/6.) \times (K1+2.0*K2 + 2.0*K3 + K4) \)
156 IF \((LB .EQ. L)\) GO TO 801
157 GO TO 200
158 C M=NO, N=NO
159 C
160 C 503 CONTINUE
161 P1(ML,NI) = EXP(-ABA * TIME)
162 WRITE (6,102) L, N, ML, NL, P1(ML,NI)
163 GO TO 200
164 504 IF \((N .EQ. NBP)\) GO TO 505
165 C M=MBP, N=NP
166 C
167 C
168 C K1 = ANJ \times P2(ML1,NI)
169 C K2 = ANJ \times 0.5 \times (P1(ML1,NI) + P2(ML1,NI))
170 C K3 = K2
171 C K4 = ANJ \times P1(ML1,NI)
172 C P1(ML,NI) = P2(ML,NI) + (H/6.0) \times (K1 + 2.0*K2 + 2.0*K3 + K4)
173 GO TO 200
174 C M=MBP, N=NP
175 C
176 C 505 CONTINUE
177 C P1(ML,NI) = 0.0
178 GO TO 200
179 C
180 C N=NO, M=MBP, NO
181 C
182 C
183 C 508 K1 = ANJ\times P2(ML1,NI) - ABA\times P2(ML,NI)
184 C PT = ANJ \times 0.5 \times (P1(ML1,NI) + P2(ML1,NI))
185 C K2 = PT - ABA \times (P2(ML,NI) + H*0.5*K1)
186 C K3 = PT - ABA \times (P2(ML,NI) + H*0.5*K2)
187 C K4 = ANJ \times P1(ML1,NI) - ABA \times (P2(ML,NI) + H*K3)
188 C P1(ML,NI) = P2(ML,NI) + (H/6.0) \times (K1 + 2.0*K2 + 2.0*K3 + K4)
189 IF \((LB .EQ. L)\) GO TO 802
190 GO TO 200
191 C
192 C
193 C N=NP, 4 N=NP, M=HO
194 C
195 C
196 C 507 CONTINUE
197 C K1 = BM1 = P2(ML,NI)
198 C K2 = BM1 \times 0.5 \times (P1(ML,NI) + P2(ML,NI))
199 C K3 = K2
200 K4 = BM1 = P1(ML,NI)
PI (ML, NL) = P2 (ML, NL) + (H/6.0) - (K1 + 2.0*K2 + 2.0*K3 + K4)
GO TO 200
C
ALSO M=NO, N=NBP, NO
C
6D1 CONTINUE
IF((BE.LT.I.).AND.(KK.GT.9)) GO TO 255
C
COMPUTE PTT IF BE > 0 & KK < 10
C
PTT=BAE
DO 250 IND=1,KK
XIND=IND
PTT=PTT*BE/XIND
250 CONTINUE
GO TO 260
255 PTT=0.
260 CONTINUE
KK = KK + I
IF((ABS(PI(ML,NL) -PTT)) .LE. EPSPTT) GO TO 199
GO TO 700
C
M=MBP, N=NO
C
802 CONTINUE
IF(RE.LT.1.).AND.(JJ.GT.9)) GO TO 270
C
COMPUTE PTT IF RE > 0 & JJ < 10
C
PTT=BAE
DO 265 IND=1,JJ
XIND=IND
PTT=PTT*RE/XIND
265 CONTINUE
GO TO 275
270 PTT=0.
275 CONTINUE
JJ = JJ + I
IF((ABS(PI(ML,NL) -PTT)) .LE. EPSPTT) GO TO 199
700 CONTINUE
C
TIME REDUCED 1/2
C
L=L-1
C
WRITE (6,701) TIME, M, N, H
C
701 FORMAT(5X,'H VALUE IS REDUCED BY 1/2 AT TIME = ',F8.3,
1 ' M = ',I5, ' N = ',I5, ' H = ',F8.3 /1
C
H = 0.5 * H
C
WRITE (6,102) L,M,N,KK, PTT, PI (ML,NL), OFK, OFJ, QQ, OFLAG
251 102 FORMAT(/ 2X, 41S. 7F12.5)
252     QFLAG=0.
253     GO TO 52
254 199 P1T=P1(ML,NL)
255 200 CONTINUE
256     QD=QD+P1(ML,NL)
257 300 CONTINUE
258 400 CONTINUE
259     QQ=ABS(QQ-1.)
260     IF(QQ1.LE.EPSQ1) GO TO 401
261     QFLAG=1.
262     GO TO 700
263 401 CONTINUE
264 C
265 C COMPUTE VARX(T), VARY(T), NSAR(T), MBAR(T), Q(T)
266 C
267     SM3 = 0.
268     SM8 = 0.
269     SQ = 0.
270     SM2 = 0.
271     SN2 = 0.
272     DO 415 MI = 1, NS
273     RM = VM(MI)
274     RM2 = RM+RM
275     DO 410 NI = 1, NS
276     RN = VM(NI)
277     RN2 = RN+RN
278     PT = PI(MI,NI)
279     P2(MI,NI) = PT
280     SM8 = SM8 + RM*PT
281     SN8 = SN8 + RN*PT
282     SQ = SQ + PT
283     SM2 = SM2 + RM2*PT
284     SN2 = SN2 + RN2*PT
285 410 CONTINUE
286 415 CONTINUE
287     VMB(L) = SM8
288     VNB(L) = SN8
289     VQ(L) = SQ
290     VARX(L) = SM2 - SM8+SM8
291     VARY(L) = SN2 - SN8+SN8
292 C
293 C RETURN TO MAIN LOOP (50) IF NOT TIME TO PRINT
294 C
295 C IF (N3D .LT. 1) GO TO 430
296 C IF (LB.ME.L) GO TO 430
297 C IF (LB.EQ.2) GO TO 430
298 C
299 C ADJUST X,Y,VECTORS FOR PLOT
300 C
DO 15 K=1,MS
15 EST(K)=K-1

DO 16 K=1,NS
16 CONTINUE

CST(1)=1

CETERM(1)=1

DO 115 J=1,41

PC(J)=0.0

115 CONTINUE

DO 116 I=1,NS

WRITE (6,199) I,PI(I,1),PI(I,2)

199 FORMAT(1',15,10X,2F15.5)

116 CONTINUE

DO 18 J=1,MS

DO 18 I=1,NS

IF(PHI(I,J).GT.PMAX) PMAX=PI(I,J)

18 CONTINUE

CONST=8.0/PMAX

DO 19 I=1,MS

N=I-MBP

19 CONTINUE

CON0=8.0/PMAX

DO 20 J=1,NS

M=J+MBP

P(I,J)=CONST*PI(I,J)

20 CONTINUE

PC(N,M)=PI(I,J)

TOTAL CONTINUE

CALL PLTSO1(CST,MP,CETERM,NS,PC,ALP,BETA,F,TTL,SIZE,WK,ION,KX,KY,N)

430 CONTINUE

C

430 CONTINUE

C

PLOT HERE

RETURN TO MAIN LOOP

GO TO 50

500 CONTINUE

DO 501 I = 1,MS

501 CONTINUE

DO 501 J = 1,NS

501 CONTINUE

PI (MS,NS) = 1.0

501 CONTINUE

GO TO 401

C
C FINAL TIME REACHED
C 210 CONTINUE
WRITE(6,211) TIME, TIM, L
211 FORMAT(1X, 'COMPUTED TIME ', F10.3, 5X, 'INPUT FINAL TIME ',
        1 F10.3, 5X, ' # OF LOOPS TO REACH FINAL TIME ', IS /, I)
DO 215 I = 1, L
WRITE(6,213) VMB(I), VNB(I), VQ(I), VAX(I), VAY(I), TIM(I)
213 FORMAT(2X, 12F10.5)
215 CONTINUE
650 FORMAT('1 ')
651 CALL PLOTP(TIM, VMB, L, 0)
652 CALL PLOTP(TIM, VNB, L, 0)
653 CALL PLOTP(TIM, VAX, L, 0)
654 CALL PLOTP(TIM, VAY, L, 0)
655 WRITE(6,650)
656 WRITE(6,650)
657 WRITE(6,650)
658 WRITE(6,650)
659 CALL PLOTP(TIM, VMB, L, 0)
660 CALL PLOTP(TIM, VNB, L, 0)
661 CALL PLOTP(TIM, VAX, L, 0)
662 CALL PLOTP(TIM, VAY, L, 0)
663 STOP
664 DEBUG SUBCHK
665 END
APPENDIX B

1 C THIS PROGRAM CALCULATES THE STATE PROBABILITIES FOR THE EQUAL
2 C ATTRAITION RATE COEFFICIENT SOLUTION (EPARS).
3 C A 3-D PLOT IS PRODUCED USING THE VERSATEC PLOTTER.
4 C
5 IMPLICIT REAL*8 (A-H, O-Z)
6 CALL ERASE (208.256.10.1)
7 DIMENSION C (50, 50), M (50), N (50), F (50), PTMN (50, 50)
8 REAL*4 SIZE (2), FL (2), MK (41, 41, 3), X (41, Y (41), P (41, 41)
9 DIMENSION KX (100), KY (100)
10 LOGICAL*1 IDN (41, 41)
11 REAL*8 TTI (12), R (12)
12 REAL*8 TTL (12) / 12*
13 READ (5, 100) MD, MBP, NO, NBP
14 READ (5, 101) A
15 READ (5, 102) TIME
16 READ (5, 103) (F (II), I = 1, 41)
17 C
18 C F (I)*1/I-FACTORIAL. DONE TO SPEED UP THE PROGRAM
19 C
20 WRITE (6, 802) MD, MBP, NO, NBP, A, TIME
21 802 FORMAT (*2.415, 2F10.5)
22 MD=MD-MBP
23 NO=NO-NBP
24 MD0=MD+1
25 NDO=NO+1
26 MBP1=MBP+1
27 NBP1=NBP+1
28 MBP2=MBP+2
29 NBP2=NBP+2
30 RHO=NO
31 RHO=NO
32 DO 10 I = 1, 41
33 DO 10 J = 1, 41
34 C (I, J) = 0.0
35 PTMN (I, J) = 0.0
36 P(I, J) = 0.0
37 10 CONTINUE
38 C (MD0, NDO) = 1.0
39 DO 20 I = 2, MD
40 J=MBP+1
41 C(I, J) = RHO*(MD-1)*1
42 20 CONTINUE
43 DO 21 I = 2, NO
44 J=NBP+1
45 C(MD0, J) = RHO*(NO-1)*1
46 21 CONTINUE
47 DO 22 I = 2, NO
48 J=MD0-1
49 MM=MD0-1
50 MPLUS=MM*1
DO 22 J=2, ND
   NC=ND1-J
   NN=ND1-J+1
   NPLUS=NN+1
   C(MM,NN)=C(MPLUS,NN)*HC + C(MM,NPLUS)
22 CONTINUE
C END OF COEFFICIENT CALCULATION
C
F1=-A*TIME
DO 60 I=MBP2, NO1
   DO 60 J=NB2, NO1
      IJ=I+J
      K=I+IJ+2
      F2=F1*0.0-DEXP(F1)*I+K
      KK=K+1
      IJ=IJ+2
      F3=DEXP(F1)*IJ
      FTMN(I,J)=F2+F3+C(I,J)*F(KK)
60 CONTINUE
25 CONTINUE
100 FORMAT (415)
101 FORMAT (F10.5)
102 FORMAT (F10.5)
103 FORMAT (017,11)
C FOR NBP<N<NO
DO 30 I=1, NO
   NFORCE=NBP-I
   IJ=M*N*I-NBP+1-NFORCE
   FACT=M*N*I-FACT
   SUM=SUM+EXP(F1)*FACT.I/FACT I
   SUMINT=SUMINT+SUM
30 CONTINUE
NMBP=J+1
NBOUND=NFORCE+1
PFAC=A*NFORCE+F(NMBP)=C(MBP2,NBOUND)
PTMN(MBP), NBOUND=PFAC*SUMINT
30 CONTINUE
C FOR MBP=M+MD

DO 40 11=1,MD
MFORCE=MBP+1
J+MD-MBP-1-MFORCE
FACT=MBP+1.0-MFORCE
SUM1=1.0-EXP (F1=FACT1/( A-FACT)
SUMINT=SUM1
DO 401 K=1,J
FACT=FACT+1.0
ADDFAC=(-1.0)**K
FRACTN=1.0-EXP (F1=FACT1/( A-FACT)
COMBT=1.0
DO 402 KJ=1,K
RKJ=KJ
COMBI= (J-RKJ+1.0)/RKJ
CMBT=COMBT+COMBI
402 CONTINUE
SUMINT=SUMINT+ADDFAC*FRACTN*COMBT
401 CONTINUE

MNBP=J+1
MBOUND=MFORCE+1
PFRC=MFORCE+F (MNBP) *C (MBOUND,MBP2)
PHN=MBOUND,MBP1) *PFRC*SUMINT
40 CONTINUE
DO 45 I=MBP1,MD
DO 45 J=NBPI,NO1
K=1-1
L=J-1
WRITE (6,801)K,L,PTMN(I,J)
801 FORMAT( ' P(I,' ,15,' ,',15,') = ',8(1X,F17.11)
45 CONTINUE
C
C DATA ADJUSTMENT FOR PLOT
NROW=41
NCOL=41
NKXT=100
LINES=0
ALPHA=15.
BETA=30.
FL(1)=0.0
FL(2)=0.0
SIZE(1)=6.0
SIZE(2)=8.0
C
C SCALING
PMAX=PTMN(1,1)
151      DO 50 I=1,41
152      X(I)=1
153      DO 50 J=1,41
154      Y(J)=J
155      IF(PTMN(I,J).GT.PMAX) PMAX=PTMN(I,J)
156      50 CONTINUE
157      CONST=8.0/PMAX
158      DO 51 I=1,41
159      P(I,J)=SNGL(CONST*PTMN(I,J))
160      51 CONTINUE
161      C
162      C IF OTHER FORCE LEVELS CHANGE PLOT ARGUMENTS
163      C
164      CALL PLT301X, NROI, T, NCOL, P, ALPHA, BETA, FL, TTL, SIZE, WK, ION, KX, KY, NKXI, LINES!
165      C
166      C EXPECTED VALUES AND VARIANCES
167      C
168      EM=0.0
169      EMM=0.0
170      VARN=0.0
171      VARM=0.0
172      SPROB=0.0
173      DO 60 I=MBP1, M01
174      I=I+1
175      SPT=0.0
176      DO 60 J=MBP1, M01
177      SPT=SPT+PTMN(I,J)
178      60 CONTINUE
179      EM=EM+SPT
180      EMM=EMM+SPT
181      SPROB=SPROB+SPT
182      VARN=EMM-EM=EM
183      VARM=VARN=0.0
184      EN=0.0
185      DO 70 I=MBP1, M01
186      I=I+1
187      SPT=0.0
188      DO 70 J=MBP1, M01
189      SPT=SPT+PTMN(I,J)
190      70 CONTINUE
191      EM=EM+SPT
192      EMM=EMM+SPT
193      SPROB=SPROB+SPT
194      70 CONTINUE
195      VARN=VARN-EN=EN
196      WRITE(6, B05) EM, EN, VARN, VARM
197      805 FORMAT(' ', 'EXPECTED VALUES M, N', ' ', 'VARIANCE M, N')
201      WRITE (8,1100) SPAB
202      1100 FORMAT(' SUM OF PROBABILITIES ',F8.2)
204      STOP
205      END
LIST OF REFERENCES


11. WEISS, H. K., Lanchester-Type Models of Warfare, Proc. First International Conference on Operational Research, M. Davis, R. Edison, T. Page (Editors), ORSA, Baltimore, Maryland, 1957.
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