A study on combat process simulation and casualty forecasting based on system dynamics

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Abstract. The traditional casualty prediction method is of low accuracy, and there is no prediction of the detail time and place of the casualty. Moreover, there is no consideration of the real combat environment. This study uses system dynamics method to build casualty forecasting model, based on the dynamic combat process of red and blue troops to predict the temporal and spatial distribution of casualty. The simulation results are similar to the one actual case. Results show that the modern combat has short duration and the total number of casualties declined over the past but the casualty is concentrated in a short period of time, and attributed in wider areas. Air forces and relative military strength are the key influence factors for casualty. The use of system dynamics model for casualty prediction can significantly improve the pertinence and effectiveness of medical support.

1. Introduction

Personnel loss of armed forces incurred by the absence in war power in combat is referred to as the casualty. Regarding modern warfare, life of soldiers is particularly precious. Therefore, scientific prediction on casualties in combat can provide support for medical service, contribute to rational allocation of health resources, improve both pertinence and timeliness of military medical service and save more soldiers.

Casualty forecasting is featured with complexity, non-linearity and fuzziness. Since the Second World War (WWII), casualty forecasting has attracted great research attention in all countries. Relevant research methods consist of statistical approaches such as regression analysis, ridge estimate and principal component analysis, operation research approaches such as Lanchester equations, quantified judgment method of analysis and quantified judgment model (QJM), etc., and computer-aided simulation approaches.

However, there are some issues of these methods. Casualty forecasting investigations by traditional statistical approaches are of low prediction precision and high statistical errors; besides, when combat environment, combat mode and weaponry change, etc, historical data is no longer suitable for casualty forecasting future combat. The operation research approaches and battle simulation neglect many factors such as the engagement process and variations of tactics. Most parameters are set at constant values so that they cannot be dynamically adjusted in line with combat process. Finally, the existing casualty forecasting research methods can only predict the casualty rate, but it is difficult to predict dynamic casualty (e.g., temporal and spatial distribution), which is unbenevolent for accurate guarantee of medical resources.

System dynamics (SD) model is a set of differential equations perfectly appropriate for describing casualty in combat. The combat process was simulated based on system dynamics in this paper to
concisely reflect engagement rules and changes of tactics on the whole. On this basis, target damages of the red and the blue forces during their engagement were analyzed to derive casualties respectively. In this manner, while casualties of both forces could be predicted, casualty distribution in time, space and concrete combat units was subdivided simultaneously; in addition, reasons why casualties were caused in each combat unit were also analyzed in details. This is the latest and an effective approach to such investigations.

2. Casualty Forecasting Model Design Based on System Dynamics

2.1. Model Structure

Causal loop diagram for this model is given in figure 1.

![Causal loop diagram for model](image)

**Figure 1.** Graphical diagram of casualty during engagement of red and blue forces.

Fundamental casualty of this model can be described as follows.

1. The increase in blue force attack ability will weaken the defense of the red force, resulting in red force casualties and reducing the red force’s attack ability, which reduce the blue force’s defensive pressure and increase blue force attack ability;
2. Similar reinforcing loop exists for red force.

These two reinforcing loops reveal that red and blue forces take advantage of weapons to attack the opponent in combat, which results in weaponry wrecking, the occurrence of personnel losses and the reduction in warfighters and weaponry quantities further attacking abilities of both forces; consequently, the relevant combat intensity goes down and the casualty rate of both forces decreases.

3. The increase of blue force defence ability stands up to red force’s attacks, reducing the blue force’s rate of casualty and increase the the blue force defence ability;
4. Similar reinforcing loop exists for red force.

These two reinforcing loops signify that armament and personnel protection conducted by blue and red forces in combat can counteract weapon attacks launched by the opponent to save arm force and weaponry so that either force has more sufficient power to attack its opponent.

Additionally, influencing factors such as physioclimate, geographical conditions, morale and training, etc. all exert affect the attacking or defensive abilities of blue and red forces. Four loops above elaborate basic logical relationship between blue and red forces during the combat.

2.2. Model Stock-flow Analysis

2.2.1. Subsystems for Confrontation Between Blue and Red Forces. Simulation software AnyLogic 7.3.6 University was utilized to construct the SD model for the purpose of describing dynamic changes of army force and casualty in combat. According to real combat practice and army troop grouping, multiple pairs of encountering groups are established with different engagement rules and parameter settings. Here, the most simplified engagement relationship between two groups selected from the blue and the red forces respectively was taken as example for description, as shown in figure 2.
Figure 2. A schematic stock-flow diagram of confrontation between red and blue forces.

This figure proves that casualties of both forces depend on a differential equation constituted by the remaining armed force and the rate of personnel loss, that is,

\[
\begin{align*}
\frac{d(RF_A)}{dt} &= - CR_A \\
\frac{d(RF_B)}{dt} &= - CR_B
\end{align*}
\]

Where, stock RF_A or RF_B stands for the remaining armed force of the red or the blue, stock DF_A or DF_B for the depletion of both forces, and parameters IF_A, Att_A and Def_A for the initial armed force, the attacking ability and the defensive ability of the red during a combat. As for CR_A and CR_B, they are casualty rate of both forces and can be figured out according to equations below.

\[
\begin{align*}
CR_A &= CAE_BAtoRA \times ERE_BAtoRA \times OCE_B \times RF_B / IF_BA \\
CR_B &= CAE_RAtoBA \times ERE_RAtoBA \times OCE_R \times RF_RA / IF_RA
\end{align*}
\]

The meanings and the calculation of the variables CAE_RAtoBA, OCE_R and ERE_RAtoBA, they will be introduced below in detail.

2.2.2. Rule of Engagement. Engagement rules can be subdivided into direct-aimed weapon based and long-range striking weapon based engagement rules. Dynamic variables ERE_RAtoBA and ERE_BAtoRA presented above are functions involved with the former, used to quantify and work out engagement rule and tactics variations in ground combat force attack and defense processes of the blue and the red. As for the stock-flow diagram for calculating such parameters, as shown in figure 3, it reflects that engagement rule settings for all ground combat groups of the red and the blue. Due to space limitations, only computing methods of ERE_RAtoBA and ERE_BAtoRA is were presented in this study.
Figure 3. A stock-flow diagram of direct-aimed weapon based engagement rules.

In this figure, Distance_RA and Distance_BA represent the distance from squads of the red and the blue to their targets separately. Besides, real-time speeds of them are denoted as Speed_RA and Speed_BA; and, Range_RA and Range_BA are both effective reaches of their weapons. Speed of the red force is subjected to the influence of its distance to the blue force and the range of the latter, etc.. When the red force falls into the range of the blue force, the latter has an ability to attack its target in the red force through direct-aimed weapons, so that attacks initiated by the red force are delayed and its attacking speed declines. In this case, speed of the blue should be adjusted according to its distance to the red force. If the distance is excessively small, the blue force should retreat in a manner of and war and the withdrawal depending on multi-level defensive positions and layers of resistance. In terms of engagement rules for a combat unit in the red or the blue force, the relevant dynamic variables ERE_RAtoBA and ERE_BAtoRA can be worked out in line with the following equations.

\[
\begin{aligned}
ERE_RAtoBA &= (Distance_RA - Distance_BA) > Range_RA?0: (Distance_RA - Distance_BA) \leq y_m \\
y_m &= \frac{Range_RA}{x_i} \times \frac{x_m}{(Distance_RA - Distance_BA)} \times \frac{1}{y_1}
\end{aligned}
\]

\[
\begin{aligned}
ERE_BAtoRA &= (Distance_RA - Distance_BA) > Range_BA?0: (Distance_RA - Distance_BA) \leq y_n \\
y_n &= \frac{Range_BA}{x_i} \times \frac{1 - ERE_BCtoRA}{x_j} \times \frac{Range_BA}{x_j} \times \frac{1}{(Distance_RA - Distance_BA)}
\end{aligned}
\]

2.2.3. Operational Constraint Quantification Subsystem. Operational constraint quantification subsystem is applicable to calculating influencing factors on the operation. The corresponding stock-flow relationship has been shown in figure 4.
Figure 4. A stock-flow diagram of operational constraint quantification.

Dynamic variables of OCE_R and OCE_B as 2 influencing factors on combat are calculated involving multiple parameters and other dynamic variables. Concrete calculations are as follows.

\[
\begin{align*}
OCE_R &= (Logistical_R \times x_1 + Intelligence_R \times x_2 + Training_R \times x_3 + Morale_R \times x_4) \times Combat_mode \times Topography \times Climate \\
OCE_B &= (Logistical_B \times x_5 + Intelligence_B \times x_6 + Training_B \times x_7 + Morale_B \times x_8) \times Combat_mode \times Topography \times Climate
\end{align*}
\]

According to the model, subsystems of indirect-aimed weapon based engagement rule settings and ammunition depletion were established to figure out artillery and air attack effects and ammunition expenditure in combat. Concrete casualties can be projected into the map according to parameters such as speed and distance, etc. of both forces as the combat progresses, where online Google Map and offline maps are applicable.

2.3. Model Parameter and Dynamic Variable Construction

2.3.1. Calculation of Attack and Defense Capabilities. Parameter calculation is mainly concerned with attack and defense capabilities of diverse combat groups in blue and red forces, including att_RA and def_RA. It consists of 3 steps.

1. Weapon performance parameterization. Regarding the attack capability, 5 indexes were selected, namely, striking distance, striking frequency, armor-piercing depth, lethal radius and hit accuracy; and, the defense capability incorporates 5 other indexes of armoring thickness, camouflage, active defense, dimension and maneuverability. Concrete values of these parameters were acquired from relevant literature.
2. Parameter indexation. Parameters of the same category of a single weapon should be all exponentiated in line with an identical standard to guarantee comparability of attack and defense capabilities among different weapons.

3. Index normalization. Exponential indexes measuring a property of the weapon were normalized into one cardinal index by drawing a radar map and calculating the area of this map.

After parameters of a single piece of equipment have been figured out, weighted sum should be obtained according to weaponry and combat forces of the relevant combat group to acquire the overall operational effectiveness of these groups from the red or the blue force. Finally, operational effectiveness was substituted into the corresponding parameter in the model.

2.3.2. Parameter Calculation for Combat Influence Factors. Such calculation is mainly concerned with 5 parameters mentioned above, namely, training, morale, combat mode, native topography and environmental climate of both forces. Firstly, analytical hierarchy process (AHP) was utilized to define weight coefficients of above influence factors. Subsequently, combat mode was selected as a dependent variable, but native topography and environmental climate as independent variables, to quantify beneficial or adverse influence incurred by the last two parameters on combat process subjected to various operational conditions by an expert consultation method. Finally, values obtained were substituted into parameters in the combat influence factor quantification subsystem to run the model.

2.3.3. Combat Attrition Calculation Equation Construction. Lanchester’s 2nd linear law widely accepted throughout the world was selected, optimized and adjusted to calculate dynamic variables of combat attrition, including CAE_RAtoBA and CAE_BAtoRA. The specific computational method is as follows.

\[
\begin{align*}
\frac{dx(t)}{dt} &= -\alpha x(t)y(t) \\
\frac{dy(t)}{dt} &= -\beta x(t)y(t)
\end{align*}
\]

Where, \(x\) and \(y\) separately stands for instantaneous forces (or remaining forces) of the blue and the red at \(t\) moment; and, \(\alpha\) and \(\beta\) for relative areas of engagement.

\[
\begin{align*}
CAE_{RAtoBA} &= \frac{-x_0(k-1)}{e^{-\alpha y_0(k-1)t} - k} \\
CAE_{BAtoRA} &= \frac{-y_0(k-1)e^{-\alpha y_0(k-1)t}}{e^{-\alpha y_0(k-1)t} - k}
\end{align*}
\]

\(k\) refers to a specific value between combat effectiveness of the blue and the red. To be concrete, \(RF_{Rx}\) and \(RF_{Bx}\) are the existing armed forces of a particular group for each at \(t\) moment; \(Att_{Rx}\) is the initial value of the attack capability of a group from the red; and, \(Def_{Bx}\) is the initial value of the defense capability of a group from the blue. Concrete formula of \(k\) is given below.

\[
k = \frac{\beta \times RF_{Rx} \times Att_{Rx}}{\alpha \times RF_{Bx} \times Def_{Bx}}
\]

Combat attrition calculation equation construction only based on the Lanchester Equation has certain limitations. For example, the combat is deemed as a definite procedure for modeling irrespective of dynamic changes in attrition coefficients, weapon suppression effects, topographic influence and the spatial distribution of forces, and human factors such as morale and training, etc..

In this study, the basic Lanchester Equation was used as a dynamic variable to propose a system dynamics model preferably solving above problems. For example, weapon depletion and personnel losses are incurred simultaneously in the process of SDM running; therefore, it can be pointed out that attrition rate keeps changing along with simulation process and relevant stocks, which effectively overcomes a deficiency that the attrition rate should be maintained at the same when only the Lanchester Equation is utilized to figure out the attrition. Moreover, cooperative combat situations of
battle groups, engagement rules, morale, training, topography and climate and other influence factors were all introduced into the model to modify and optimize the simple Lanchester Equation.

3. Simulation Result Analysis

3.1. Analysis on Engagement Processes and the Overall Situation of Combat Casualties

In accordance with the combat mode, combat simulation was carried out. Parameters such as force allocation of the red and the blue were set up before the simulation according to the scenario. Through the comparison with actual combat data, the simulation results were proven to basically coincide with the physical truth. The total casualties and attrition rates of the blue and the red have been presented in figures 5 & 6, in which, the vertical coordinate refers to the number of people and the horizontal axis to time (unit: minute).

At the beginning of a battle, artillery and air strikes of the blue and the red focus on zones where armed forces have been built up. Such a combat mode can lead to massive casualties at the very start. The first peak of attrition occurs when the red force breaks through the front line of the blue force. At this time, their ground forces begin to fight against each other for the first time. As for the second attrition peak, it takes form when the red advances toward the reserve position of the blue from the front line. Under the circumstance that the red force breaks through such a reserve position, the 3rd attrition peak appears. According to the figure, broken line in blue goes above that in red for the first time at the moment when the battle continues for 65 minutes; in this case, reserve force of the red join the battle, giving rise to substantial casualties among defensive forces of the blue so that attribute rate of the blue exceeds that of the red.

![Figure 5. Total casualties of the combat between the blue and the red forces.](image_url)

![Figure 6. Attrition rate of the combat between the blue and the red forces.](image_url)
Temporal distribution of red group casualties caused by all kinds of weapons of the blue has been given in figure 7, where the vertical coordinate refers to the number of people and the horizontal axis to time (unit: minute). A major reason why curves of casualties incurred by the indirect-aimed weapon and air strikes on the main attack squad, the secondary attack squad and the reserve force of the red vary is that, when ground forces of the red and the blue fight hand-in-hand at an excessively short distance, their long-range strike forces begin to transform their extensive planar strikes into precise dotted attacks to prevent accidental injuries giving rise to operational effectiveness reduction.

**Figure 7.** Line charts of the relationship between combat casualties and the time related to all red groups.

Quantitative distribution of red group casualties caused by all kinds of weapons of the blue has been given in figure 7, where the vertical coordinate refers to the number of people and the horizontal axis to time (unit: minute). Casualties of the red force caused by air power of the blue take a percent of more than 40% in the total casualty of the red ground force and a percent of above 70% in those of troops in the rear such as the artillery group and the security assistance squad, etc. This phenomenon reflects huge power exerted by air strikes and the importance of air defense and air supremacy seizure.

**Figure 8.** Attrition reason analysis charts for combat groups of the red force.

### 3.3. Relevant Parameter Adjustment for Operational Test

Sensitivity analysis on the model was carried out to determine that antiaircraft fire intensity parameter of the red force and military strength comparison parameter of the ground force were two parameters
with the most significant influence on simulation results. During contrast experiment after above parameters have been adjusted, their impacts on battle results and attrition were observed.

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