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Operational Effectiveness Evaluation of the Swarming UAVs Combat System Based on a System Dynamics Model

NIPING JIA, ZHIWEI YANG, AND KEWEI YANG
College of Systems Engineering, National University of Defense Technology, Changsha 410073, China
Corresponding author: Zhiwei Yang (zhwyang88@hotmail.com)

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ABSTRACT Currently, the new operational tactic of the swarming unmanned aerial vehicles (UAVs) combat is becoming a hotspot in military research, and evaluating the combat efficiency and the roles of UAVs is of vital importance for the future development of UAVs. However, most of the recent studies on the swarming UAVs combat are merely qualitative analyses. This paper proposes an operational effectiveness evaluation method of the swarming UAVs combat system based on a system dynamics (SD) model. The weapons in the combat process are divided into nine subsystems and we build corresponding nine in-trees models using the rate-variable in-trees modeling method. The final SD model is established based on the nine in-trees and the characteristics of swarming UAVs are considered. Taking the surviving rate of UAVs and task completion degree as the evaluation indicators, the model simulation shows that over 50% of the enemy ground targets can be destroyed in 15-time units, although some UAVs may be damaged. It is also confirmed through comparison experiments with other combat patterns that the swarming UAVs play a crucial role in improving the system combat efficiency and can decompose the function of traditional high-value weapon platforms.

INDEX TERMS Effectiveness evaluation, swarming UAVs combat, system dynamics model, rate-variable in-tree modeling method.

I. INTRODUCTION

Recently, a new operational pattern of the swarming unmanned aerial vehicles (UAVs) combat is attracting worldwide attention for its advantages of strong autonomy, low cost, high flexibility, and fast upgrading [1]–[3]. On the battlefield, a large number of small UAVs will assume the responsibilities of sensors, attackers, or baits through information sharing and coordination, and can decompose the functions of traditional large and expensive equipment, such as electronic reconnaissance aircrafts and fighters, to some extent [4], [5]. Currently, many countries are engaged in the development and application of the swarming UAVs technology and have conducted numerous studies, experiments, and demonstrations. For example, the US Air Force released the first roadmap for the development of the swarming UAVs system and illustrated the missions of small drones, including suppression/destroy enemy air defense systems and coordinated strike and reconnaissance, and the related projects include Gremlins, LOCUST, Perdix, and CICADA, etc. [6]–[8]. One of the primary tasks of these projects is how to evaluate the role of UAVs in the battle quantitatively compared with the traditional combat patterns and make a scientific plan for the future development of UAVs.

So far, many scholars have studied the new swarming UAVs combat style, but most of them are qualitative analyses, such as the report on swarming UAVs confrontation by Luo D, in which he reviewed recent studies on the swarming UAVs combat style, summarized the key techniques, and discussed the features and future development of the swarming UAVs [9]. There are also some quantitative studies, but the focus is mainly on the task allocation strategy and UAVs route planning. For example, Li and Zhang. [10] proposed a dynamic ant colony's labor division model and performed numerical simulations to determine the best-distributed task allocation. The particle swarm

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optimization algorithm with differential evolution operations and adaptive weight strategies was applied in the path planning of UAVs [11].

However, studies on the effectiveness assessment methods of swarming UAVs, which are of vital importance for the demonstration of unmanned equipment development, are scant. At present, although there are many modeling and evaluation methods of the combat system, most of these models are not applicable to the swarming UAVs combat system considering the unique features of UAVs, and the main problems include

(1) When developing the model, the information flow relationship among different pieces of equipment must be considered, which is crucial to the modeling of the swarming UAVs system.

(2) Most of the current studies are limited to static modeling such as establishing the network of the weapon system, but they rarely include the dynamic analysis, which is also a quite important characteristic of swarming UAVs.

System Dynamics (SD) modeling theory, first proposed by Forrester [12]–[14], can help to meet the challenges of modeling the information communication and dynamic relationship of UAVs by adding feedbacks and the time variable to the model, which is a typical method to study the structure and behavior of a system. By combining the system theory and computer simulation, it can help reveal the internal causes of swarming UAVs system and predict the future development of the system.

Currently, the SD model is mainly applied to social problems, such as economics, sustainability, and manufacture [15]. Nevertheless, it also shows flexible advantages in analyzing the combat system by the graphic structure and the establishment of equations, and can simulate the complex relationships among the system components. In most cases, data about the war may be inadequate, which is often a problem in combat system modeling. The SD model is established according to the feedbacks among system components and has less dependence on the battlefield data. It provides a good quantitative perspective for analyzing the swarming UAVs combat system and can help provide policy guidance to decision-makers.

Considering the unique features of swarming UAVs combat system, this study aims to demonstrate a method to create a simple SD model for the swarming UAVs combat system and evaluate the combat effectiveness of UAVs to support the development of UAV equipment.

The remainder of the paper is organized as follows. In Section II, the swarming UAVs combat system is first described and analyzed. The SD modeling process and the operational effectiveness evaluation indicators are illustrated in Section III. The simulation results and the analysis of model parameters are provided in Section IV. Section V provides the conclusion and describes the future works.

Many commercial software programs can be used to create the SD model. In this study, we use *Vensim* to establish the model and perform simulations.

II. SYSTEM ANALYSIS

This section aims to introduce and describe the swarming UAVs combat system and make a causality analysis of the system elements to provide a foundation for the establishment of the SD model.

A. SYSTEM DESCRIPTION

In 2016, the US Air Force magazine published a document on small UAVs flight planning [16], and defined the swarming UAVs combat system: A group of small drones (can be both congeneric or heterogeneous) will conduct unified combat missions through autonomous networking under the supervision of the controller, and can cooperate with various manned aircraft and weapons.

In the combat process, the transport planes are usually deployed in the rear side of the formation and carry some UAVs, which will be released to the battle continuously. The UAVs perform the roles of baits, sensors, and attackers, and can cooperate with traditional aircraft and weapons to execute the combat mission. At the beginning of the combat, the bait UAVs will be disguised as fighters and attract the enemy fire, and simultaneously, the reconnaissance UAVs will acquire the enemy information and transfer it to the decision-making platforms such as the early-warning airplane. The decision weapons will process the information and perform the task allocation to launch an attack on the enemy. Subsequently, the attack UAVs and fighters will receive the instructions and use bombs, missiles, and other similar weapons to carry out the task. All the above manned and unmanned platforms constitute the swarming UAVs combat system, and the UAVs play a significant part in enhancing the combat efficiency.

From the above description, it can be concluded that, compared with the traditional combat pattern, the swarming UAVs combat system has unique features, which must be reflected in the SD model. The main characteristics of UAVs include, but are not limited to [17]

(1) Strength in numbers: In the swarming UAVs combat system, there are numerous UAVs to decompose the function of traditional large and expensive weapons, and it can be reflected in the initial force parameter settings in the process of model establishment.

(2) Low cost: The manufacturing expense of small UAVs is much lower than that of manned fighters; hence, once the UAVs are damaged, they will not be recycled temporarily and the new UAVs can be supplemented to the battlefield continuously to compensate for the force loss. This feature will be considered in the SD model through the supplement factor.

(3) Coordination: The autonomous synergy is one of the most crucial characteristics of the swarming formation, and

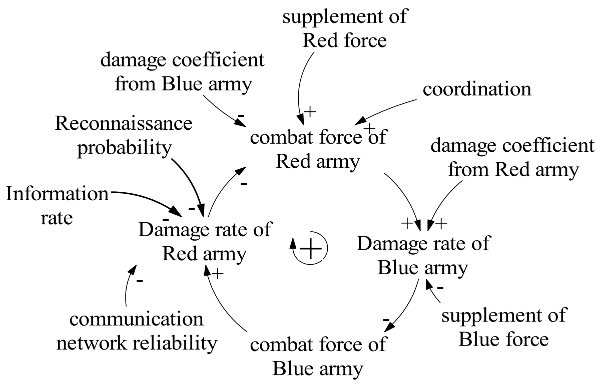

FIGURE 1. **Causality analysis of the system.**

the UAVs will communicate and coordinate with each other during the combat process instead of working alone, which has to be reflected in the model.

B. CAUSALITY ANALYSIS

Causality analysis is a basic step for SD modeling, helping to determine the relationships among system components and providing a foundation for establishing the SD stock-flow model [18]. The swarming UAVs combat system is first divided into Red (attacker) and Blue (enemy) armies, and the force change of both sides is the main factor representing the combat efficiency [19].

Fig. 1 is a causality diagram revealing the relationships of the system components, and the negative and positive feedbacks are indicated by arrows. The combat force of Red army can be influenced by the communication reliability, the reconnaissance probability, the information acquisition rate, the coordination, the force supplement, and the enemy attack ability, among which the enemy attack ability will have a negative effect on the Red force. The influencing factors of the Blue army may include the force supplement and the attack ability of the Red army weapons, and the force supplement has an evident positive effect on the combat efficiency of the Blue side.

Notably, here we only figure out the influencing system factors and their causality relationships to obtain a general impression of the system instead of focusing on the specific weapons. Further analysis of weapons relationships will be provided in Section III based on the causality diagram.

III. SYSTEM MODELING BASED ON RATE-VARIABLE IN-TREE METHOD

A. METHODOLOGY

Most SD models are established through causal graphs and stock-flow models to show the relationships among system components. However, the modeling process of the stock-flow diagram is based on the analysis of the subsystems, attempting to determine level-rate pairs in subsystems, and gradually adding variables to the structural model [20]. The eventual stock-flow model is often quite complex and difficult to interpret. Therefore, in this paper, we use the rate-variable fundamental in-tree method to build the system stock-flow model, which is based on the correspondence between the SD model structure and the differential equation. Namely, every differential equation matches a subsystem. This method makes the modeling process clearer and easier to understand, and can help interpret the establishment process of the stock-flow model. Although the rate-variable in-tree method has been applied in various fields and has achieved good performance, it has few applications in the operational system, especially in the new combat tactic of swarming UAVs combat. This work provides a new perspective on the modeling and assessment of the swarming UAVs combat system.

1) INTRODUCTION OF SYSTEM DYNAMICS RATE-VARIABLE IN-TREE MODELING METHOD

The rate-variable fundamental in-tree is a modeling method based on reductionism, first proposed by Jia *et al.* [21]. It divides the system into many subsystems, and the level, rate, and auxiliary variables are set in every subsystem. In the subsystem, a rate variable is generally set as the root of a tree model and other variables are added to the tree, which describes the causal relationships among variables. The final system stock-flow model can be constructed by the subsystem trees through the embedded operation. The definitions of the rate-variable in-tree and the embedded operation are as follows [22].

Definition 1: The rate-variable in-tree

Supposing that there is a dynamic directed graph $T(t) = [V(t), X(t)]$, $v(t) \in V(t)$ is a point in the graph, if $u(t) \in V(t)$ and there is only one directed road from $u(t)$ to $v(t)$, then the directed graph $T(t)$ is called a tree. In the SD graph $T(t)$, if the rate variable is the root of the tree and the level variable is set as the end of the tree, then $T(t)$ can be called a rate-variable in-tree.

Definition 2: The embedded operation

Supposing that two sub-flow graphs $G_1(t)$ and $G_2(t)$ are represented by two fundamental in-trees respectively, to obtain a new combined graph $G(t)$, we define the embedded operation $\overrightarrow{U}$, such that

$$G(t) = G_1(t)\overrightarrow{U}G_2(t) \tag{1}$$

where $G(t)$ is the merged graph of $G_1(t)$ and $G_2(t)$ after eliminating the repeated variables and relationships. The embedded operation $\overrightarrow{U}$ satisfies the following properties:

Commutativity:

$$G_1(t)\overrightarrow{U}G_2(t) = G_2(t)\overrightarrow{U}G_1(t) \tag{2}$$

Associativity:

$$[G_1(t)\overrightarrow{U}G_2(t)]\overrightarrow{U}G_3(t) = G_1(t)\overrightarrow{U}[G_2(t)\overrightarrow{U}G_3(t)] \tag{3}$$

2) STEPS OF MODELING

Based on the above concepts, the SD modeling process steps are provided as follows.

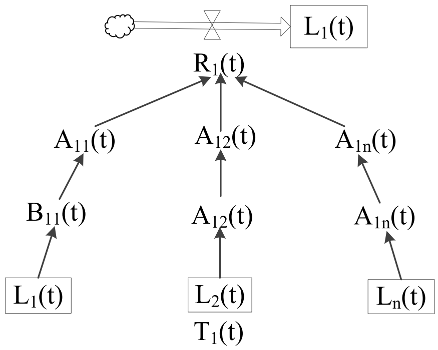

FIGURE 2. Rate-variable fundamental in-tree of a subsystem.

TABLE 1. Weapons in the battle.

Id	Red army (Attacker)
1	Reconnaissance UAVs
2	Attack UAVs
3	Bait UAVs
4	Fighters
5	Missiles
Id	**Blue Army (Enemy)**
6	Interceptors
7	Air defense missile
8	Antiaircraft artillery
9	Ground targets

Step 1: Analyze the system based on the causality diagram, and set the level-rate variables system:

$$\{[L_1(t), R_1(t)], [L_2(t), R_2(t)], \ldots, [L_n(t), R_n(t)]\}$$

Step 2: Divide the system into several subsystems and establish rate-variable in-trees for every subsystem. In every in-tree, $R_i(t)$ is the root of the tree and $L_i(t)$ is the end of the tree, as Fig. 2 shows.

Where, A_{ij} and B_{ij} are auxiliary variables.

Step 3: Use the embedded operation for the in-trees $T_1(t), T_2(t), \ldots, T_n(t)$ to merge the vertexes and arcs, and obtain the final system stock-flow model.

Step 4: Use the final SD model (stock-flow model) to perform simulation and evaluate the combat efficiency.

B. ESTABLISHMENT OF LEVEL AND RATE-VARIABLES SYSTEM

1) CONFRONTATION RELATIONSHIP ANALYSIS

In the swarming UAVs combat scene, we assume that the targets are the enemy ground command center and infrastructure. The weapons involved in the combat are illustrated in Table 1.

2) LEVEL AND RATE-VARIABLES SYSTEM

From the above weapons, we can extract the level and rate variables in the SD model. The level-rate system is as follows:

The number of reconnaissance UAVs $L_1(t)$, the quantity variation rate of reconnaissance UAVs $R_1(t)$;

The number of attack UAVs $L_2(t)$, the quantity variation rate of attack UAVs $R_2(t)$;

The number of bait UAVs $L_3(t)$, the quantity variation rate of bait UAVs $R_3(t)$;

The number of fighters $L_4(t)$, the quantity variation rate of fighters $R_4(t)$;

The number of missiles $L_5(t)$, the quantity variation rate of missiles $R_5(t)$;

The number of enemy interceptors $L_6(t)$, the quantity variation rate of interceptors $R_6(t)$;

The number of enemy air defense missiles $L_7(t)$, the quantity variation rate of air defense missiles $R_7(t)$;

The number of enemy antiaircraft artillery $L_8(t)$, the quantity variation rate of antiaircraft artillery $R_8(t)$;

The number of targets $L_9(t)$, the quantity variation rate of targets $R_9(t)$.

Moreover, in the rate-variable tree of the combat system, there are some auxiliary variables, including the overall attack and defense ability coefficients of Red or Blue army (C_i), the weapons apportion coefficients (K_{ij}), and the damage capability coefficients (d_{ij}).

The overall attack and defense ability coefficients (C_1, C_2, D_1, D_2) represent the warfare combat ability of the Red or Blue army. Here, C_1 indicates the offensive ability of the attacker (Red army), and C_2 indicates the offensive ability of the enemy (Blue army). D_1 represents the defense capability of the attacker, and D_2 represents the defense capability of the enemy. The ratio C_1D_1/C_2D_2 is used for indicating the comprehensive combat ability of the Red army compared with that of the enemy.

The weapons apportion K_{ij} represents the force allocation proportion of the force i (when combating with j), and $K_{ij} < 1$. For example, if $K_{29} = 0.5$, it indicates that 50% of the attack UAVs will assault the enemy ground target, and the other 50% attack UAVs will be involved in combats with other enemy weapons.

The damage capability coefficient d_{ij} indicates the damage influence from weapon i to j, which is a basic factor derived from the Lanchester equation and has been widely used in operational system models [23].

Where, $i = 1, 2, \cdots, 9,\ j = 1, 2, \cdots, 9, i \neq j$.

C. THE RATE-VARIABLE FUNDAMENTAL IN-TREES MODEL OF THE SWARMING UAVs COMBAT SYSTEM

According to the weapon categories, we divide the swarming UAVs combat system into nine subsystems and establish nine rate-variable fundamental in-trees to illustrate the model construction process. The offensive and defensive correspondence relationships between Red and Blue army are shown in Table 2, based on which the differential equations for each in-tree can be established.

For each subsystem, assuming that $N_i(t)$ represents the force supplement of weapon $i(i = 1, 2, 3, \ldots, 9)$ and $Q_i(t)$ indicates the weapon quantity attrition with time, we can obtain the following in-trees and differential equations.

TABLE 2. Combat confrontation relationships.

Confrontation	Confrontation
1 vs. 9	6 vs. 3
2 vs. 6	6 vs. 4
2 vs. 9	7 vs. 1
3 vs. 6	7 vs. 2
4 vs. 6	7 vs. 3
5 vs. 6	7 vs. 4
5 vs. 8	8 vs. 3
5 vs. 9	8 vs. 4
6 vs. 2	

- For the Red army (attacker):

(1) Reconnaissance UAVs system

On the battlefield, the reconnaissance UAVs mainly assume the responsibility of sensing the combat situation. They are difficult to hit because of the dispersion and are often damaged by the enemy air defense missile. According to the corresponding influence factors, the in-tree is established as shown in Fig. 3.

The quantity variation of reconnaissance UAVs can be calculated as

$$R_1(t) = \frac{dL_1(t)}{dt} = N_1(t) - Q_1(t) \tag{4}$$

$$Q_1(t) = \frac{C_2D_2}{C_1D_1}[L_7(t)K_{71}d_{71}] \tag{5}$$

(2) Attack UAVs system

According to the scenario in this study, the attack UAVs will launch an attack toward enemy fighters and may be damaged by enemy defense missiles and interceptors; hence, the quantitative change of attack UAVs may be related to the level variables of $L_6(t)$, $L_7(t)$ and the corresponding factors. The in-tree of the subsystem is shown in Fig. 4.

The quantity variation of attack UAVs is given by

$$R_2(t) = \frac{dL_2(t)}{dt} = N_2(t) - Q_2(t) \tag{6}$$

$$Q_2(t) = \frac{C_2D_2}{C_1D_1}[L_6(t)K_{62}d_{62} + L_7(t)K_{72}d_{72}] \tag{7}$$

For the other subsystems, we also carefully analyzed the corresponding variables and the system influencing factors, and the remaining seven in-tree models are established as follows.

(3) Bait UAVs system

The quantity variation of bait UAVs is given by

$$R_3(t) = \frac{dL_3(t)}{dt} = N_3(t) - Q_3(t) \tag{8}$$

$$Q_3(t) = \frac{C_2D_2}{C_1D_1}[L_6(t)K_{63}d_{63} + L_7(t)K_{73}d_{73} + L_8(t)K_{83}d_{83}] \tag{9}$$

(4) Fighters system

The quantity variation of fighters is given by

$$R_4(t) = \frac{dL_4(t)}{dt} = N_4(t) - Q_4(t) \tag{10}$$

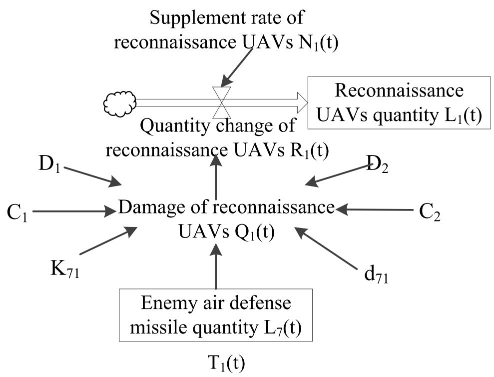

FIGURE 3. Rate-variable in-tree of reconnaissance UAVs.

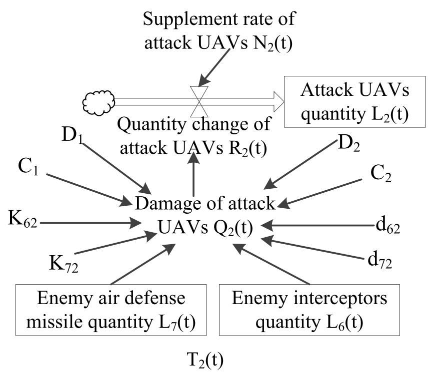

FIGURE 4. Rate-variable in-tree of attack UAVs.

$$Q_4(t) = \frac{C_2D_2}{C_1D_1}[L_6(t)K_{64}d_{64} + L_7(t)K_{74}d_{74} + L_8(t)K_{84}d_{84}] \tag{11}$$

(5) Missiles system

The quantity variation of missiles $R_5(t)$ is given by

$$R_5(t) = \frac{dL_5(t)}{dt} = N_5(t) - Q_5(t) \tag{12}$$

$$Q_5(t) = \frac{C_2D_2}{C_1D_1}[L_6(t)K_{56}d_{56} + L_8(t)K_{58}d_{58} + L_9(t)K_{59}d_{59}] \tag{13}$$

- For the Blue army (defender):

(6) Interceptors system

The quantity variation of interceptors $R_6(t)$ is given by

$$R_6(t) = \frac{dL_6(t)}{dt} = N_6(t) - Q_6(t) \tag{14}$$

$$Q_6(t) = \frac{C_1D_1}{C_2D_2}[L_4(t)K_{46}d_{46} + L_3(t)K_{36}d_{36} + L_2(t)K_{26}d_{26}] \tag{15}$$

(7) Air defense missiles system

The quantity variation of air defense missiles $R_7(t)$:

$$R_7(t) = \frac{dL_7(t)}{dt} = N_7(t) - Q_7(t) \tag{16}$$

$$Q_7(t) = \frac{C_1D_1}{C_2D_2}[L_1(t)K_{71}d_{71} + L_2(t)K_{72}d_{72} + L_3(t)K_{73}d_{73}] \tag{17}$$

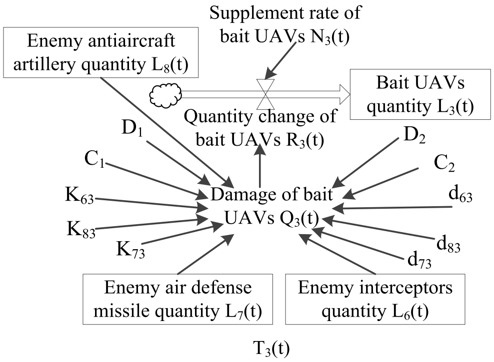

FIGURE 5. Rate-variable in-tree of bait UAVs.

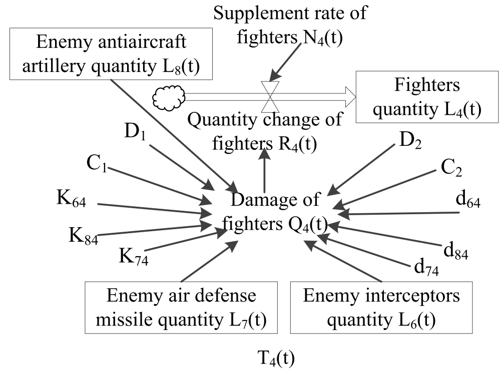

FIGURE 6. Rate-variable in-tree of fighters.

(8) Antiaircraft system

The quantity variation of antiaircraft artillery is given by

$$R_8(t) = \frac{dL_8(t)}{dt} = N_8(t) - Q_8(t) \tag{18}$$

$$Q_8(t) = \frac{C_1 D_1}{C_2 D_2}[L_5(t)K_{58}d_{58} + L_3(t)K_{83}d_{83} + L_4(t)K_{84}d_{84}] \tag{19}$$

(8) Enemy targets system

The quantity variation of targets can be represented as

$$R_9(t) = \frac{dL_9(t)}{dt} = N_9(t) - Q_9(t) \tag{20}$$

$$Q_9(t) = \frac{C_1 D_1}{C_2 D_2}[L_5(t)K_{59}d_{59} + L_1(t)K_{19}d_{19} + L_2(t)K_{29}d_{29}] \tag{21}$$

Supposing that t_0 is the start time of the combat and L_{i0} represents the initial weapon quantities, then

$$L_i(t)|_{t=t_0} = L_{i0}, \quad (i = 1, 2, \cdots, 9)$$

The force apportion coefficient K_{ij} meet the following constraints according to the offensive and defensive correspondence relationships in Table 2:

$$K_{19} = 1, \quad K_{36} = 1, \; K_{46} = 1, \; K_{26} + K_{29} = 1$$
$$K_{56} + K_{58} + K_{59} = 1, \quad K_{62} + K_{63} + K_{64} = 1$$
$$K_{71} + K_{72} + K_{73} + K_{74} = 1, \quad K_{83} + K_{84} = 1$$

D. THE FINAL SD MODEL

From the above rate-variable fundamental in-trees model of nine subsystems, we can build the SD model (stock-flow chart) through the embedded operations—namely,

$$G(t) = T_1(t)\vec{U}\,T_2(t)\vec{U}\,T_3(t)\vec{U}\,T_4(t)\vec{U}\,T_5(t) \vec{U}\,T_6(t)\vec{U}\,T_7(t)\vec{U}\,T_8(t)\vec{U}\,T_9(t) \tag{22}$$

where $G(t)$ is the final stock-flow model.

However, the SD model must reflect the typical features of the swarming UAVs system and must be differentiated from the traditional SD combat model. In the above $G(t)$, the large quantity and supplement of UAVs have been considered.

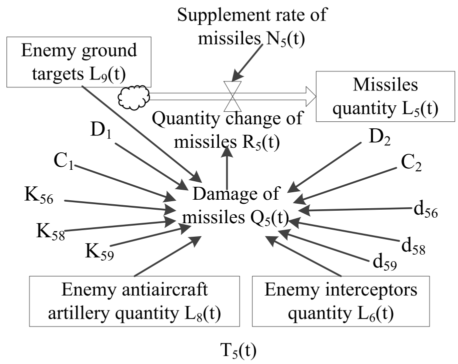

FIGURE 7. Rate-variable in-tree of missiles.

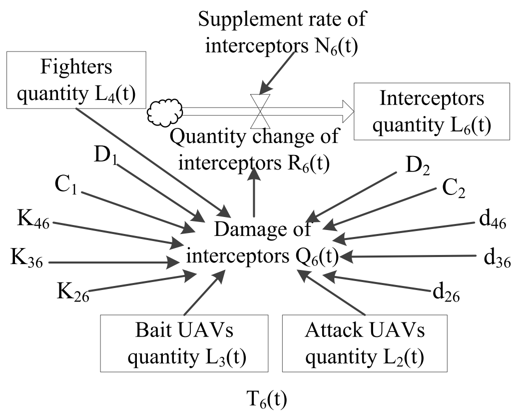

FIGURE 8. Rate-variable in-tree of interceptors.

To make the model more consistent with the characteristic of swarming UAVs, we add the following factors to the model.

(1) Information transmission rate: One of the most important features of the swarming UAVs is that they can obtain the battlefield information continuously and transmit it to the command part. Therefore, we add the factor of information transmission rate to the model to represent the information acquisition and transmission of UAVs.

(2) Coordination time: In the combat process, each UAV has the autonomous ability, and they need to synchronize the battlefield situation before executing the task. Here the coordination time represents the time for synchronization before the task.

TABLE 3. Effectiveness assessment indexes.

Indicators	Calculation method
Surviving rate of reconnaissance UAVs	$r = 1 - \frac{R_{loss}}{L_{10} + N_1(t) \times t}$
Surviving rate of attack UAVs	$a = 1 - \frac{A_{loss}}{L_{20} + N_2(t) \times t}$
Surviving rate of bait UAVs	$b = 1 - \frac{B_{loss}}{L_{30} + N_3(t) \times t}$
The proportion of destroyed targets	$g = \frac{T_{destroy}}{L_{90}}$

(3) Reconnaissance probability: It means the probability of discovering enemy targets for UAVs. In contrast to the traditional single reconnaissance aircraft, the swarming reconnaissance UAVs can share the battlefield information with each other; thus, the reconnaissance probability may be higher than that of traditional scout planes.

By adding the above factors, the final SD stock-flow model of the swarming UAVs combat system $G'(t)$ can be constructed. Fig. 12 shows the final system model, which is simplified for a better view, focusing on the complex relationships among subsystems.

E. THE SYSTEM OPERATIONAL EFFECTIVENESS EVALUATION INDICATORS

Based on the above SD model, the combat result can be predicted and we can evaluate the system operational effectiveness according to the SD simulation result.

Supposing that the total combat time is T, the numbers of damaged reconnaissance UAVs, attack UAVs, and bait UAVs until time T are R_{loss}, A_{loss}, and B_{loss}, respectively, and the total number of destroyed enemy ground targets is $T_{destroy}$, based on the above SD model, we can obtain

$$R_{loss} = \int_0^T \frac{C_2 D_2}{C_1 D_1} [L_7(t) K_{71} d_{71}] dt \tag{23}$$

$$A_{loss} = \int_0^T \frac{C_2 D_2}{C_1 D_1} [L_6(t) K_{62} d_{62} + L_7(t) K_{72} d_{72}] dt \tag{24}$$

$$B_{loss} = \int_0^T \frac{C_2 D_2}{C_1 D_1} [L_6(t) K_{63} d_{63} + L_7(t) K_{73} d_{73} + L_8(t) K_{83} d_{83}] dt \tag{25}$$

$$T_{destroy} = \int_0^T \frac{C_1 D_1}{C_2 D_2} [L_1(t) K_{19} d_{19} + L_2(t) K_{29} d_{29} + L_5(t) K_{59} d_{59}] dt \tag{26}$$

To evaluate the combat effectiveness of the combat system, the following evaluation indicators are listed in Table 3.

Where, L_{10}, L_{20}, and L_{30} indicate the initial quantities of reconnaissance, attack, and bait UAVs at the beginning of the combat, respectively; $N_1(t)$, $N_2(t)$, and $N_3(t)$ indicate the supplement rates of reconnaissance, attack, and bait UAVs, respectively.

r, a, b represents the proportions of the reconnaissance, attack, and bait UAVs that were not damaged at the end of the combat, respectively, and g is the task completion degree (the proportion of destroyed targets) of the combat, which can represent the combat effectiveness efficiently.

TABLE 4. Initial weapons quantities.

Red army (Attacker)	Quantity
Reconnaissance UAVs	40
Attack UAVs	40
Bait UAVs	30
Fighters	5
Missiles	5
Blue Army (Enemy)	**Quantity**
Interceptors	10
Air defense missiles	20
Antiaircraft artillery	20
Ground targets	60

TABLE 5. Damage coefficient definition.

Damage ability degree	Range of the damage probability value
Low	[0,0.3)
Medium	[0.3,0.6)
High	[0.6,1]

IV. MODEL SIMULATION AND RESULTS

A. MODEL PARAMETERS SETTING

Based on the above modeling, the parameters of the simulation for the swarming UAVs combat system are set as follows.

(1) Initial weapons quantities: In the swarming UAVs combat system, the initial weapons quantities for the combat are listed in Table 4.

(2) Damage capability coefficient: The damage coefficient represents the damage ability caused to the opponents. In this paper, we define the coefficient d_{ij} to be the damage probability caused from weapon system i to j. However, the data of the damage probabilities are sometimes difficult to obtain; hence, here we define the damage ability degree according to the combat ability.

In the model, we first analyze the combat capability degree of the corresponding weapons according to the expert experience, and thereafter set the values of the parameters in the model simulation as shown in Table 6. The sensitivity analysis of these parameters will be presented later.

(3) Force apportions: The constraints of K_{ij} are set according to the military confrontation relationships. For example, if the attack task of the missiles subsystem is launched to enemy interceptors, antiaircraft artillery, and ground targets—i.e., all the confrontation relationships related to missiles subsystem are 5 vs.6, 5 vs.8, and 5 vs.9, then

$$K_{56} + K_{58} + K_{59} = 1 \tag{27}$$

TABLE 6. Damage coefficient setting.

Damage probabiity	Degree	value
d_{19}	Medium	0.3
d_{26}	Low	0.05
d_{29}	Low	0.2
d_{36}	Low	0.05
d_{46}	Low	0.05
d_{56}	Low	0.1
d_{58}	Low	0.1
d_{59}	Low	0.1
d_{62}	Medium	0.4
d_{63}	Low	0.2
d_{64}	Low	0.1
d_{71}	Medium	0.4
d_{72}	High	0.6
d_{73}	Medium	0.5
d_{74}	Low	0.1
d_{83}	Low	0.2
d_{84}	Low	0.1

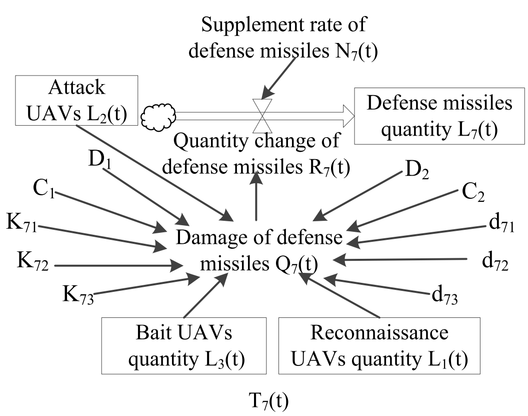

FIGURE 9. Rate-variable in-tree of defense missiles.

The value of K_{5j} is set according to the average allocation strategy, namely

$$K_{56} = K_{58} = K_{59} = \frac{1}{3} \quad (28)$$

Other parameters are set similarly according to the detailed battlefield confrontation relationships.

(4) Overall attack and defense ability coefficient of Red and Blue army: C_1 and C_2 represent the warfare attack abilities of the Red and Blue army, respectively, and D_1 and D_2 indicate the warfare defense ability of the Red and Blue army respectively ($C_1, C_2, D_1, D_2 \in [0, 1]$).

In the swarming UAVs combat system, the arms of the Red army are mainly attack weapons and the enemy mainly owns

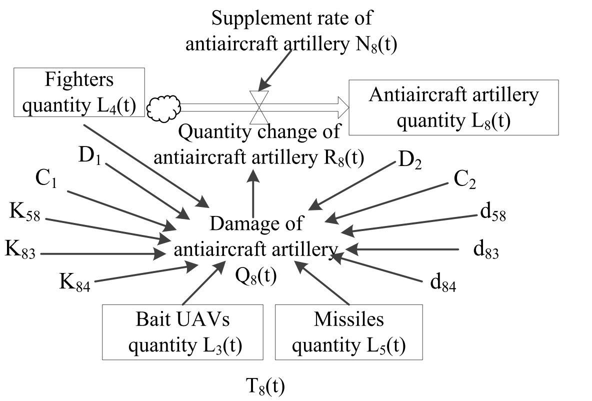

FIGURE 10. Rate-variable in-tree of antiaircraft artillery.

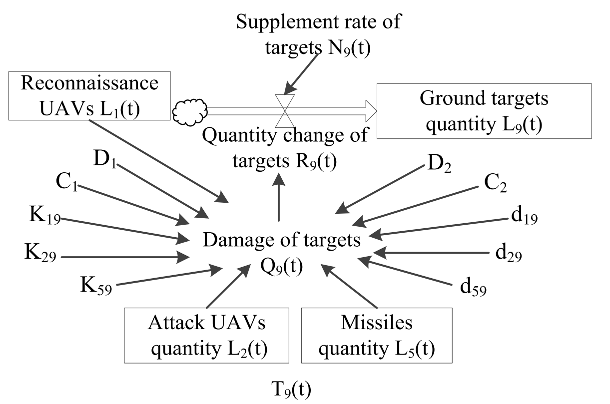

FIGURE 11. Rate-variable in-tree of targets.

defense weapons and hence, we define

$$C_1 > C_2, \quad D_1 < D_2 \quad (29)$$

Moreover, the ratio C_1D_1/C_2D_2 is used for indicating the comprehensive combat ability of the Red army compared with that of the enemy. Here, it is assumed that the comprehensive combat ability of the Red army is slightly higher than that of the Blue army considering the participation of UAVs. Thus,

$$\frac{C_1D_1}{C_2D_2} \to 1^+ \quad (30)$$

This indicates that the Red army has a slight advantage in operational capability. According to the expert experience, we set

$$C_1 = 0.26, \quad C_2 = 0.24, \ D_1 = 0.15, \ D_2 = 0.16$$

then

$$\frac{C_1D_1}{C_2D_2} = 1.01 > 1$$

(5) Coordination time of UAVs: It is a coefficient indicating the synchronization time among UAVs before executing the task, which reflects the cooperation ability of UAVs. In this model, we set it to be 0.8 seconds according to the historical

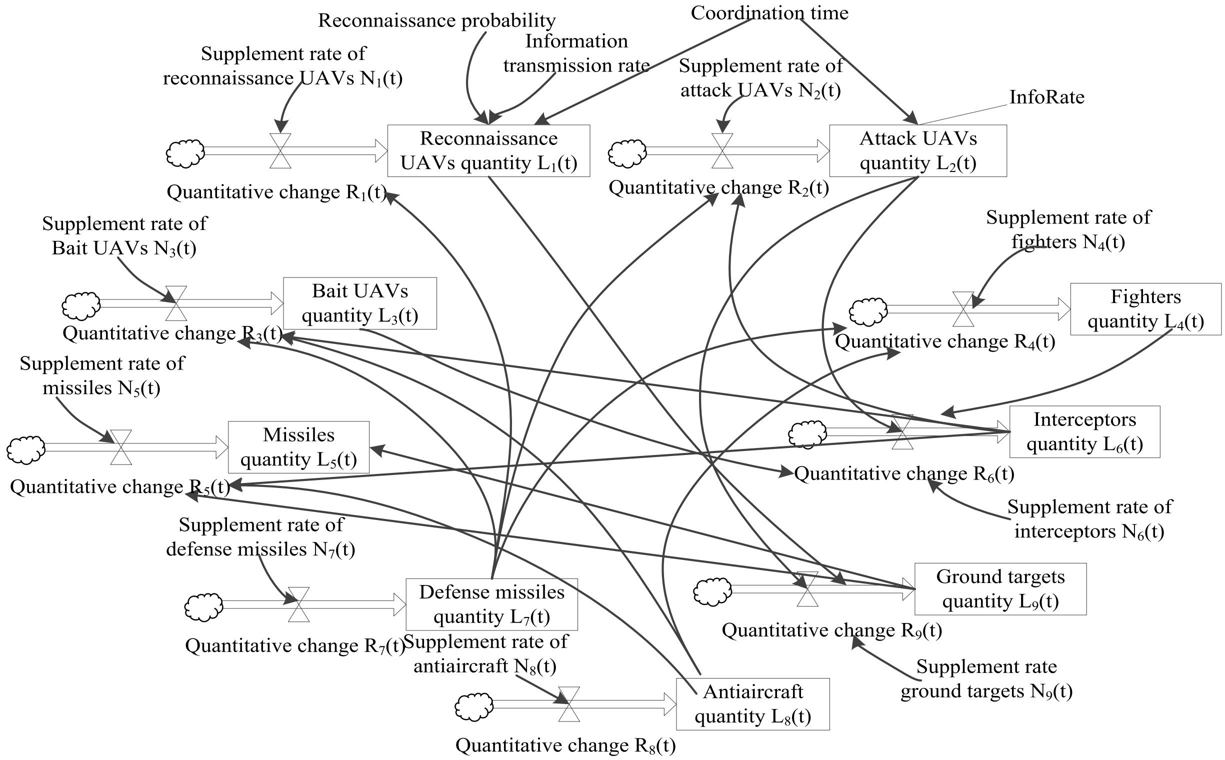

FIGURE 12. Final system stock-flow model (simplified).

combat data, and the sensitivity analysis will be presented later.

(6) Information transmission rate of UAVs: This variable indicates the information transmission ability of the UAVs, which is of great significance to the combat efficiency. Generally, the data transmission rate of UAVs is a fixed performance parameter and the value is often standardized. According to the general data of UAVs, we set it to be 25 Mbit/s in the model.

(7) Reconnaissance probability: It indicates the reconnaissance ability of reconnaissance UAVs and is set as 0.5 according to the statistics based on the history combat data of general reconnaissance UAVs.

(8) Supplement rate of UAVs: In contrast to the traditional weapons such as fighters, one of the most significant features of the swarming UAVs is their low cost and they can be supplemented during the combat process to compensate for the loss of the force. It is assumed that the bait UAVs are all released at the start of the combat and will not be replenished later, whereas the reconnaissance and attack UAVs can be supplemented once every minute, and the supplement rate is 2.

B. SIMULATION RESULT

Based on the above model and parameters, we simulate the swarming UAVs combat process in *Vensim* and obtain the following result. Assuming that the combat lasts for 15 time units, the force change of both sides is illustrated by the dotted lines in Figs. 13 and 14.

TABLE 7. Combat efficiency of the swarming UAVs combat system.

Surviving rates of UAVs			
UAVs	Reconnaissance UAVs	Attack UAVs	Bait UAVs
Force left	32.163	34.107	23.309
Indicators	*r*	*a*	*b*
Surviving	80.408%	85.268%	77.697%
Damage of targets			
Quantity	30.6859		
Indicator	*g*		
Proportion	51.143%		

It can be concluded from the result that over 50% of the enemy ground targets can be destroyed in 15 time units although some UAVs from the Red army may be damaged. The following Table 7 shows the surviving rates of UAVs and the task completion degree of the combat.

C. ROLES OF UAVs

Moreover, we wonder the roles of these swarming UAVs in the combat system and in this part, and we will compare the above simulation results with two other combat patterns—namely the general UAVs combat and the traditional combat pattern, to validate the importance of swarming UAVs.

Note that the SD model in this study is also applicable to the above two combat styles only if the types and quantities of weapons and some parameters are adjusted.

1) GENERAL UAVS COMBAT

The general UAVs combat refers to the combat system with unmanned platforms, which contains some UAVs, but the

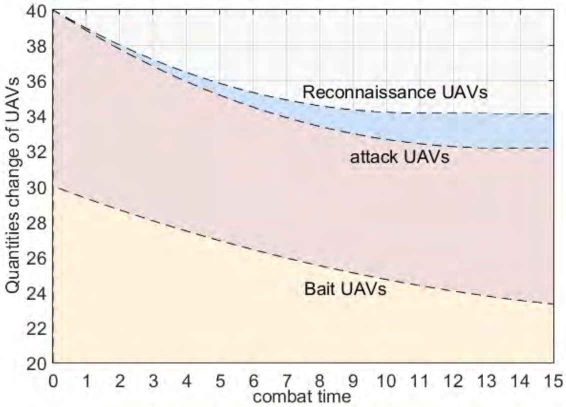

FIGURE 13. UAVs force of the Red army during the combat process.

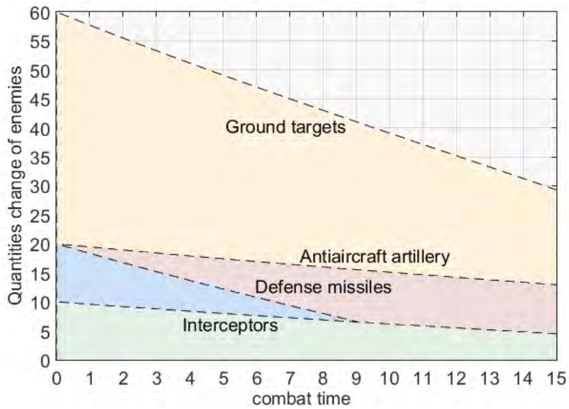

FIGURE 14. Force changes of the Blue army during the combat process.

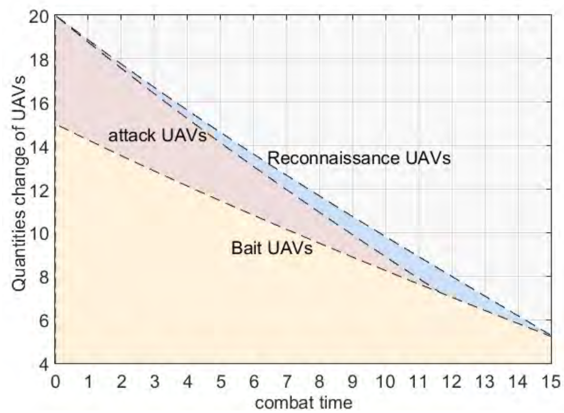

FIGURE 15. UAVs force changes in the general UAVs combat pattern.

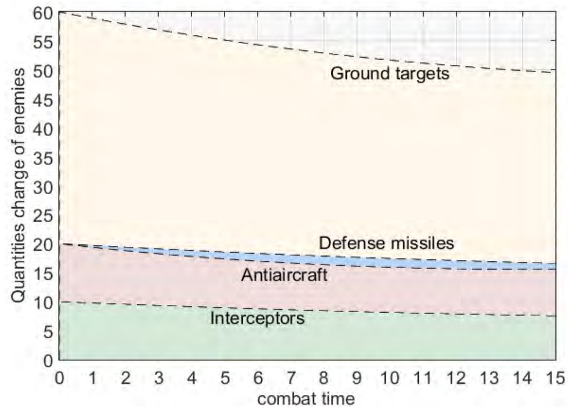

FIGURE 16. Blue force changes in the general UAVs combat pattern.

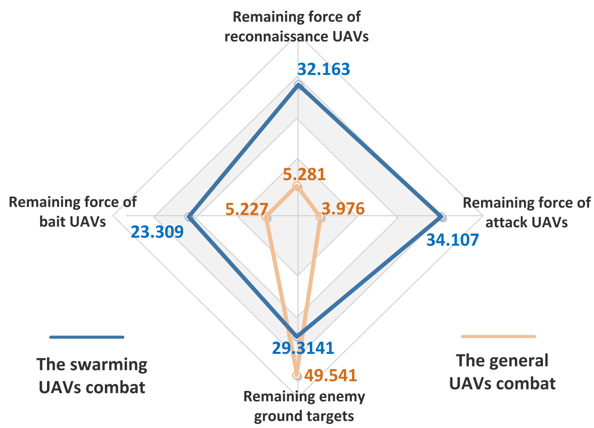

FIGURE 17. Simulation result (force left at time 15) comparison.

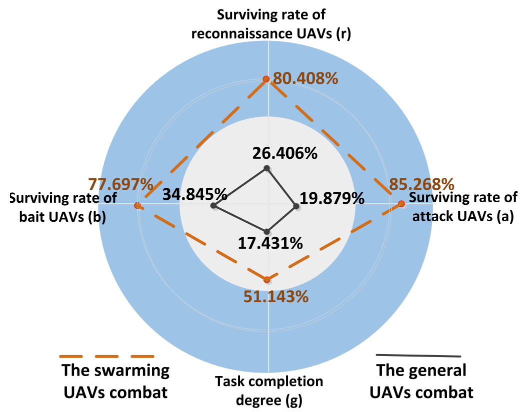

FIGURE 18. Combat efficiency indicators comparison.

quantity is not high and the UAVs cannot form the swarming formation. They are only used to assist the detection and attack tasks, and cannot coordinate with each other spontaneously.

We revised the swarming UAVs combat system model based on the characteristics of the general UAVs combat. The initial quantities of reconnaissance, attack, and bait UAVs are reduced to 20, 20, and 15, respectively, and the supplement of UAVs and coordination factors are eliminated from the model, whereas the variables and parameters of other system components are not changed. The simulation results are shown in Figs. 15 and 16.

From the simulation results, it can be observed that, in the general UAVs combat system, the total proportion of damaged UAVs is relatively higher compared with that of the

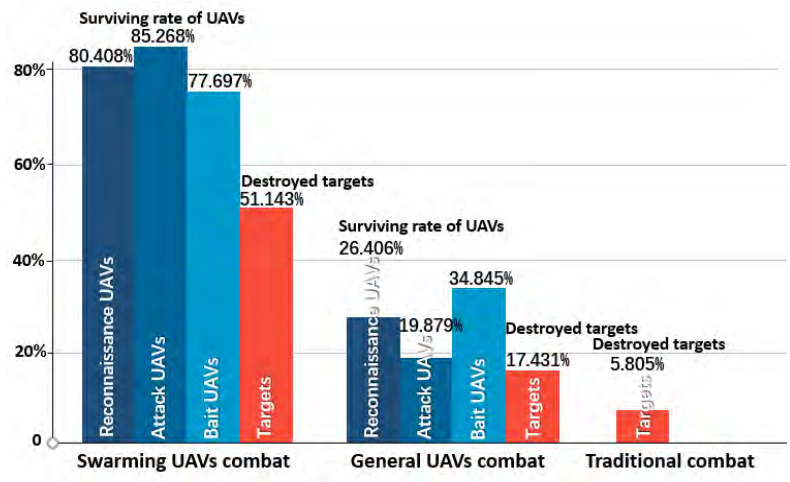

FIGURE 19. Combat efficiency comparison among the swarming UAVs combat, the general UAVs combat, and the traditional combat pattern.

swarming UAVs combat, and the quantity of destroyed enemy targets is merely approximately 10, indicating that the combat efficiency may decline remarkably if the UAVs cannot form the swarming formation.

Figs. 17 and 18 show a comparison of the battlefield results and combat efficiency data between the swarming UAVs combat and the general UAVs combat pattern. It is evident that the swarming UAVs combat has the advantages of much less UAVs force loss and higher task completion degree. The task completion degree of the general UAVs combat system is merely 17.431% and most of the UAVs will be destroyed during the combat process.

From the above comparison, it can be concluded that the swarming UAVs play a significant role in improving the system combat efficiency. If the UAVs cannot form the swarming synergy, the operational effectiveness will be reduced remarkably.

2) TRADITIONAL COMBAT STYLE

The traditional combat indicates combat with traditional large weapons without the assistance of unmanned platforms. To determine the roles of UAVs during the swarming UAVs combat process, we eliminated all the UAVs from the swarming system model and only used the traditional weapons to launch the attack, simulate the combat process, and observe the change of combat effectiveness.

In the revised traditional combat SD model, the corresponding parameters of allocation proportion coefficients will vary with the type change of weapons, and factors relating to UAVs will also be eliminated from the model. Under this circumstance, we observe that the combat efficiency will decrease more remarkably and only 5.805% of the targets can be destroyed at time 15, indicating that the attack speed will be decreased evidently without the assistance of UAVs.

Fig. 19 illustrates the operational effectiveness data of the three different combat patterns, and it is evident that the swarming UAVs combat pattern can lead to the best combat result.

On the basis of the traditional combat SD model, we also attempted to add some fighters and missiles to the Red army to compensate for the loss of swarming UAVs. Considering the proportion of destroyed targets at time 15, we observe that, after adding 15 fighters and 30 missiles, approximately 30 targets will also be destroyed, which is just similar with the result of the swarming UAVs combat, although there is a slight difference between the quantity decreasing processes of the targets in the two simulations, as shown in Fig. 20.

From the above analysis, it can be concluded that the effect of UAVs in the swarming UAVs combat system is, to some extent, equivalent to the roles of 15 fighters and 30 missiles according to the task completion degree and combat time. The result confirms the basic concept of swarming UAVs combat pattern: The swarming UAVs are designed to decompose the functions of traditional high-value weapons, and can achieve a similar combat effect with low cost and high operational flexibility.

In conclusion, through a comparison between the swarming UAVs SD model results and those of the other two combat patterns, we observe that the swarming UAVs play a crucial role in improving the combat effectiveness and are, to some extent, equivalent to the roles of traditional weapons such as fighters and missiles.

D. PARAMETER ANALYSIS

1) PARAMETER SENSITIVITY ANLYSIS

In the process of building the SD model, the parameters setting is a crucial step that may influence the model validity. Hence, we will analyze the parameters involved in the model and determine their impacts on the swarming UAVs combat system.

➢ SUPPLEMENT RATE OF UAVS

The supplement of UAVs is an important feature of the swarming UAVs combat system. In the SD model, it has been

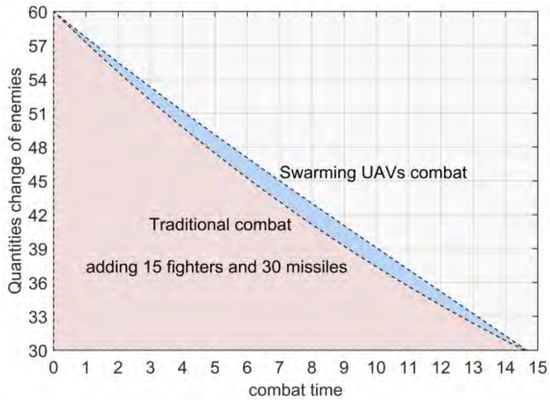

FIGURE 20. Combat efficiency after adding 15 fighters and 30 missiles to the traditional combat pattern (without UAVs) V.S. combat efficiency of the swarming UAVs combat.

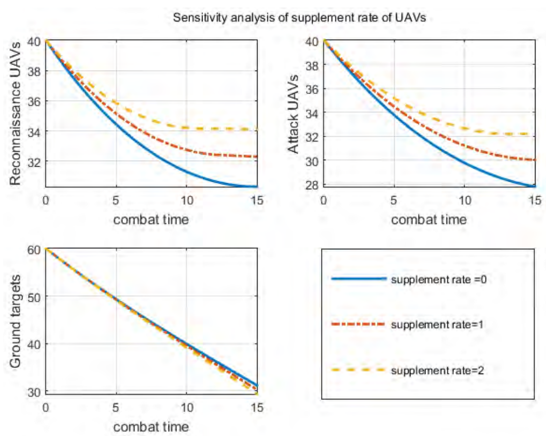

FIGURE 21. Influence of supplement rate of UAVs.

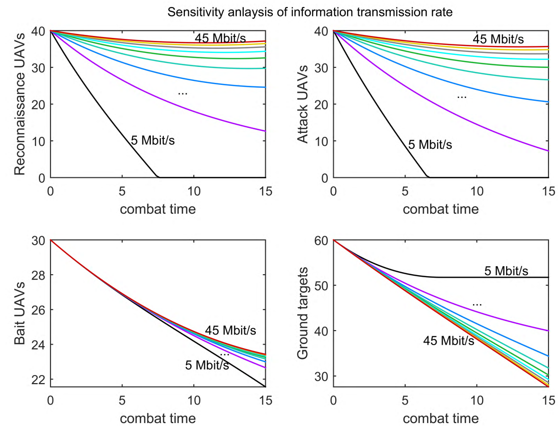

FIGURE 22. Influence of information transmission rate.

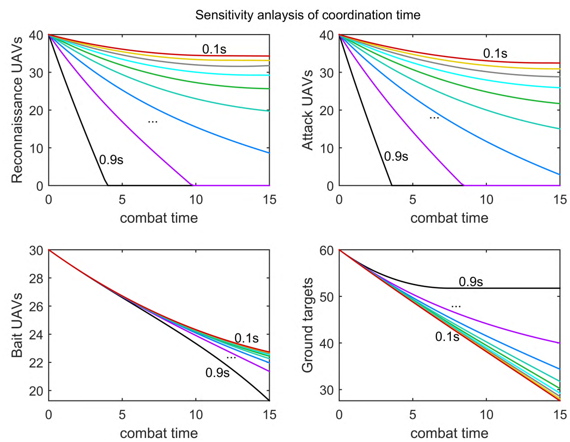

FIGURE 23. Influence of coordination time.

assumed that the bait UAVs will be launched at the beginning of the combat and will not be replenished, whereas the reconnaissance and attack UAVs can be supplemented during the combat process. The value of supplement rate is changed from 2 to 1 and 0 (per time unit), and Fig. 21 indicates that the supplement rate will mainly affect the quantity change of reconnaissance and attack UAVs, while the influence to the targets is negligible, probably because that there have been enough UAVs for the task at the beginning of the combat.

➢ INFORMATION TRANSMISSION RATE

The information transmission rate indicates the information acquiring and transmitting rate of UAVs and is set according to the performance data of UAVs in the SD model. Here, we change it from 5 Mbit/s to 45 Mbit/s (with steps of 5 Mbit/s) and obtain the following simulation results.

It can be concluded from the above simulation that the information transmission rate has a significant influence on the quantity of reconnaissance UAVs, attack UAVs, and the ground targets. As the transmission rate increases, the UAVs will acquire more information from the battle and send it back to the command post in time, thus leading to higher combat effectiveness. As is shown in Fig. 22, when the UAVs have a higher information acquiring and transmitting rate, the number of damaged UAVs at the end of the combat will decrease remarkably and more targets will be destroyed.

➢ COORDINATION TIME OF UAVS

The coordination time refers to the synchronization time among UAVs before executing the task and it also has a great effect on the combat result. Fig. 23 shows a comparison of the simulation results with the coordination time varying from 0.1 seconds to 0.9 seconds, which reveals that the impact of UAVs coordination time on the combat result is similar with that of the information transmission rate. The coordination factor in the SD model will mainly affect the force loss of reconnaissance and attack UAVs and the task completion degree, while it may have little impact on the force change of bait UAVs.

➢ RECONNAISSANCE PROBABILITY OF UAVS

Here, the reconnaissance probability represents the detection capability of UAVs, which is set as 0.5 according to the history combat data and expert experience in the SD model. Fig. 24 shows the simulations with different reconnaissance probabilities.

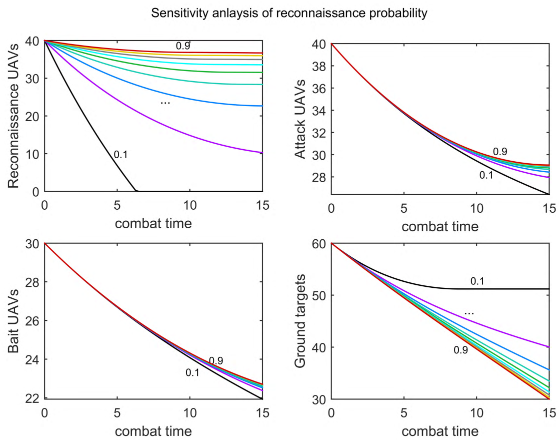

FIGURE 24. Influence of reconnaissance probability.

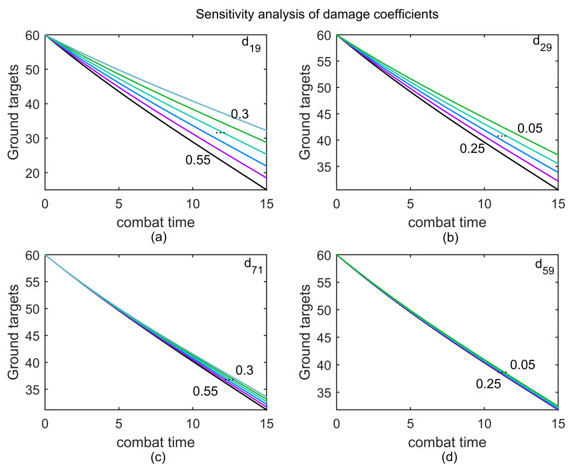

FIGURE 25. Influence of damage coefficient.

As shown in the above diagrams, as the reconnaissance capability of UAVs increases, more targets will be destroyed and the cost of reconnaissance UAVs of the combat will decrease. By contrast, the number of attack and bait UAVs will not change significantly.

➢ DAMAGE CAPABILITY COEFFICIENT

The damage coefficient is one of the most important parameters in the SD model. In this paper, we defined the damage coefficients of various weapons as the damage probabilities causing to the opponents, and they are divided into three levels: high, medium, and low.

Considering that the damage ability degree can be given based on the expert experience whereas the specific value is set by the modeler, we change the value of every damage coefficient (17 damage coefficients in total as Table 6 shows) in the range of its damage ability degree (with steps of 0.05) and simulate the combat results.

Taking d_{72} as an example, the damage degree of d_{72} is set as ''high'' in the SD model. In the parameter analysis, this damage coefficient value is changed as Table 8.

For the damage coefficients of the degree ''medium'' such as d_{19}, the values are changed as shown in Table 9.

TABLE 8. Values of d_{72}.

Experiment	1	2	3	4
d_{72}	0.6	0.65	0.7	0.75
Experiment	**5**	**6**	**7**	**8**
d_{72}	0.8	0.85	0.9	0.95

TABLE 9. Damage coefficients of medium degree.

Experiment	1	2	3	4	5	6
Values	0.3	0.35	0.4	0.45	0.5	0.55

TABLE 10. Damage coefficients of low degree.

Experiment	1	2	3	4	5
Values	0.05	0.1	0.15	0.2	0.25

For the damage coefficients of the degree ''low'' such as d_{19}, the values are changed as shown in Table 10.

According to the damage ability degree and the above three tables, we changed the damage coefficients values in the swarming UAVs SD model one by one and recorded their impacts on the combat results.

It is found that d_{19} and d_{29} will affect the task completion degree (see as (a) (b) in Fig. 25), whereas most of the remaining damage coefficients will have little influence on the combat results (like (c) (d) in Fig. 25), indicating that the operational abilities of reconnaissance UAVs and attack UAVs are of vital importance to the combat effectiveness.

Moreover, the simulation results under different damage coefficient values indicate that, in the SD model, the system behavior is not so sensitive to some parameters for the existence of various feedbacks. The model is mainly established based on the relationships among the system components. Consequently, although the combat data may be not adequate, the system behavior will show the same pattern within a tolerant parameter range.

2) DISCUSSION OF THE PARAMETER SETTING IN THE SD MODEL

From the modeling process in this paper, it can be noticed that there are many parameters in the SD model. The existence of parameters is one of the typical features of the system dynamics modeling, because it is based on the feedbacks and mathematical relationships among system variables instead of the real-time simulation. However, these parameters must be reasonable and well-founded. At present, the SD parameters in most studies are set according to the expert experience or historical data, and in this paper, we also use some expert knowledge and combat data during the parameter setting process. However, this way is sometimes not convincing enough, although we made relevant parameter sensitivity analyses. Actually, the parameters and their values can also be derived from a detailed simulation of the system, which is a good support for the SD model.

For the swarming UAVs combat system, the SD model can simulate the combat result and predict the force quantity change, but some details like the UAVs formation

TABLE 11. The Parameters Involved in the SD Model.

1	Initial weapons quantities
2	Damage capability coefficient
3	Force apportions
4	Overall attack and defense ability coefficient
5	Coordination time of UAVs
6	Information transmission rate of UAVs
7	Reconnaissance probability of UAVs
8	Supplement rate of UAVs

TABLE 12. The damage probability from weapon system i to j in the SD model.

Confrontation	sd_{ij}	d_{ij}	Confrontation	sd_{ij}	d_{ij}
1 vs. 9	sd_{19}	d_{19}	6 vs. 3	sd_{63}	d_{63}
2 vs. 6	sd_{26}	d_{26}	6 vs. 4	sd_{64}	d_{64}
2 vs. 9	sd_{29}	d_{29}	7 vs. 1	sd_{71}	d_{71}
3 vs. 6	sd_{36}	d_{36}	7 vs. 2	sd_{72}	d_{72}
4 vs. 6	sd_{46}	d_{46}	7 vs. 3	sd_{73}	d_{73}
5 vs. 6	sd_{56}	d_{56}	7 vs. 4	sd_{74}	d_{74}
5 vs. 8	sd_{58}	d_{58}	8 vs. 3	sd_{83}	d_{83}
5 vs. 9	sd_{59}	d_{59}	8 vs. 4	sd_{84}	d_{84}
6 vs. 2	sd_{62}	d_{62}			

cannot be well reflected, which requires significant efforts of multi-agent detailed simulations. However, the multi-agent simulation and the SD simulation are two different scopes. The detailed simulation is more concrete, while the SD is relatively abstracted, mainly focusing on the mathematical relationships of system components and the combat result prediction. Nevertheless, the factors of damage probability and coordination time of UAVs, etc. can be get from the detailed simulation under the condition of UAVs formation and weapon collaboration, and can serve as the parameter input of the SD model.

Table 11 illustrates all the parameters included in the SD model of this paper. The initial weapons quantities, the force apportions, and the supplement rate of UAVs are usually given by the modeler or the decision maker at the beginning of the simulation (for both the SD simulation and the detailed simulation). The information transmission rate of UAVs is a basic performance attribute of UAVs and the value is often standardized, which can also be set at the beginning of the model simulation. The remaining four kinds of parameters (the damage capability coefficient, the overall attack and defense ability coefficient, the coordination time of UAVs and the reconnaissance probability of UAVs) can be obtained from the multi-agent detailed simulation.

1) The damage capability coefficient (d_{ij}) is used to represent the combat influence from weapon system i to $j (i = 1, 2, \cdots, 9, \quad j = 1, 2, \cdots, 9, i \neq j)$. In the SD model, we defined it as the damage probability from weapon system i to j (e.g. the damage probability of Blue army missiles to the attack UAVs of Red army), and set the value according to the expert experience by defining three damage ability degrees. However, the damage probability can also be obtained from the simulation. Generally, the one-to-one damage probability of the weapon (e.g. one defense missile to one attack UAV) is set in advance of the detailed simulation, but it may be not equal to the overall damage probability among corresponding weapon systems because of the UAVs formation or cooperation factors. Thus, the damage probability from weapon system i to$j$ requires to be obtained from the detailed simulation results. For example, if we set the damage probability from a missile of the Blue army to an attack UAV of the Red army as 0.5 before the simulation, it doesn't mean that the damage probability from the missiles system to the attack UAVs system will also be 0.5, because in the process of the combat, the UAVs will share information and coordinate with each other, and may also have collaboration with manned weapons, which will help to reduce the harm from the enemy missiles. Hence, we can rely on the detailed simulation to get the overall damage probability from weapon system i to j, which will serve as the input of the damage capability coefficient in SD model.

2) The overall attack and defense ability coefficient (C_1, C_2, D_1, D_2) in the SD model is used to represent the warfare combat ability of the Red or Blue army. They can also be defined and acquired from the simulation result besides the expert experience.

In table 12, sd_{ij} represents the average damage probability from weapon system i to j set before the simulation, d_{ij} indicates the damage probability acquired from the simulation results. Then, the overall attack ability coefficient (C_1 for Red army and C_2 for Blue army) can be defined as the average damage probability acquired from the simulation results. Namely,

$$C_1 = (d_{19} + d_{26} + d_{29} + d_{36} + d_{46} + d_{56} + d_{58} + d_{59})/8 \tag{31}$$

$$C_2 = (d_{62} + d_{63} + d_{64} + d_{71} + d_{72} + d_{73} + d_{74} + d_{83} + d_{84})/9 \tag{32}$$

The overall defense ability coefficient (D_1 for Red army and D_2 for Blue army) can be defined as the average defense rate due to the weapon cooperation. For the reconnaissance UAVs system, the damage rate caused from the enemy air defense missile system before the simulation is set as sd_{71}, the actual damage rate after the simulation is d_{71}, then $sd_{71} - d_{71}$ can be regarded as the defense rate of the reconnaissance UAVs system due to the formation and collaboration with manned weapons, which can represent the defense capability of the reconnaissance UAVs to the enemy defense missile system to some extent. For the Red and Blue army, the defense ability coefficients can be obtained by

$$D_1 = \frac{1}{9}((sd_{62} - d_{62}) + (sd_{63} - d_{63}) + (sd_{64} - d_{64}) + (sd_{71} - d_{71}) + (sd_{72} - d_{72}) + (sd_{73} - d_{73}) + (sd_{74} - d_{74}) + (sd_{83} - d_{83}) + (sd_{84} - d_{84})) \tag{33}$$

$$D_2 = \frac{1}{8}((sd_{19} - d_{19}) + (sd_{26} - d_{26}) + (sd_{29} - d_{29}) + (sd_{36} - d_{36}) + (sd_{46} - d_{46}) + (sd_{56} - d_{56}) + (sd_{58} - d_{58}) + (sd_{59} - d_{59})) \tag{34}$$

3) The coordination time of UAVs in the SD model is defined as the synchronization time of the UAVs before executing the task. In the SD model, we set the parameter value according to the historical combat data. However, the historical data is often acquired merely from the UAVs combat (not the swarming UAVs combat pattern). As a result, if the parameter can be obtained from the detailed simulation of the swarming UAVs combat process, it will be more reliable and convincing.

4) The reconnaissance probability of UAVs in the SD model indicates the average probability of detecting the targets for reconnaissance UAVs system, which is related to the UAVs detecting performance and the enemy camouflage or stealth ability. The reconnaissance probability can also be acquired through the detailed simulation of the swarming UAVs combat besides the historical combat data.

In conclusion, the detailed multi-agent simulation can provide a solid and reliable support for the process of establishing and simulating the SD model, especially for the parameter setting work. In this way, not only the parameters setting process can be more convincing and reliable compared with traditional expert or historical data methods, but also the UAVs formation and cooperation issues among manned and unmanned weapons can be reflected by the parameters of damage probability and coordination time, because they are obtained through the detailed simulation of the swarming UAVs combat considering the coordination factors.

Actually, the SD modeling and the multi-agent simulation are at two different levels of abstraction. The first is to describe the global structure and feedbacks of the system, whereas the agent-based simulation focuses on the individual behavior. This paper is aimed to use the SD model to evaluate the combat effectiveness and assess the role of UAVs in the swarming UAVs combat system, not to simulate the detailed combat process. As a result, the detailed simulation may be out of the scope of the paper. However, the SD model can still be supported and replenished if there is a detailed simulation, which will enhance the model credibility and scientificity remarkably. The connection of the SD model and the detailed simulation will be an interesting and meaningful work in the future, and we will conduct the multi-agent detailed simulation of the swarming UAVs combat system to support our SD model in our future studies.

V. CONCLUSION AND FUTURE WORKS

This paper presented an operational effectiveness evaluation method of the swarming UAVs combat system based on a System Dynamics (SD) model. Taking the surviving rate of reconnaissance, attack, and bait UAVs and the proportion of destroyed targets as the evaluation indicators, the model simulation result showed that, in the swarming UAVs combat, over 50% of the enemy ground targets can be destroyed in 15 time units, although some UAVs may be damaged. Moreover, to determine the role of UAVs, we compared the model simulation results with those of two other combat patterns: the general UAVs combat and the traditional combat. It is validated that the UAV swarms are indispensable for improving the combat efficiency and their role is, to some extent, equivalent to the function of traditional high-value weapon platforms such as fighters and missiles. The influencing parameters of the warfare were analyzed after the SD simulation. The experiments indicated that the UAVs supplement, the information transmission, the coordination and the higher reconnaissance ability will all have a positive effect on improving the combat efficiency in various degrees, whereas the combat result is not much sensitive to most of the damage coefficients within the tolerant parameter range.

Moreover, we discussed the relationship between the SD simulation and the detailed simulation of the swarming UAVs combat system. Some of the parameters in SD model can be acquired from the multi-agent detailed simulation, which will help to make the modeling process more convincing and scientific. However, the detailed simulation and the connection of the two kinds of simulations require significant efforts, which will be an innovative and interesting work in the future study.

The proposed SD model in this paper helps to assess the significance of swarming UAVs from a new quantitative perspective and can provide a theoretical support for the demonstration of unmanned equipment development. In the future work, we will conduct a detailed simulation of the swarming UAVs combat system to study the formation and collaboration issues better, and modify the SD model based on the data of detailed simulation results.

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NIPING JIA received the B.S. degree in management science and engineering from the National University of Defense Technology, Changsha, China, in 2017, where she is currently pursuing the M.S. degree with the College of Systems Engineering. Her current research interests include complex networks, system dynamics modeling and application, and system of systems modeling.

ZHIWEI YANG received the B.S. and M.S. degrees from the National University of Defense Technology, Changsha, Hunan, China, in 2010 and 2012, respectively, and the Ph.D. degree in computer science from Leiden University, in 2016. He is currently a Lecturer of management science and engineering with the National University of Defense Technology. His research interests include the intelligent optimization method and system of systems optimization.

KEWEI YANG received the B.S. degree in systems engineering and the Ph.D. degree in management science and engineering from the National University of Defense Technology, Changsha,Hunan, China, in 1999 and 2004, respectively. From 2011 to 2012, he was a Visiting Scholar with the Department of Computer Science, University of York, York, U.K. He is currently a Professor of management science and engineering and the Director of the System of Systems Engineering Laboratory. His research interests include intelligent agent simulation, defense acquisition, and system of systems requirement modeling.