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Research on Modeling of Parallel Closed-loop Support Process for Carrier Aircraft Based on System Dynamics

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Abstract

The support process of carrier aircraft is a complex closed-loop system with time delay and parallelism. At present, the related literature is lack of research on parallel closed-loop system. Since System Dynamics is a method that can reveal the dynamic process of complex system. Therefore, this paper proposes a modeling method of parallel closed-loop operation based on System Dynamics. The support process model for carrier aircraft is established in order to analyze the parallel closed-loop system of carrier aircraft. The flow chart and the system structure equations of support process are presented for analysis of the dynamic process and the static performance. The simulation is based on the actual data of Nimitz Aircraft Carrier. The influences of fueling operation, weapons loading operation, other operations and strike task on support capacity are simulated and analyzed. The bottleneck factors affecting support capacity are found through simulation and analysis. A new evaluation method of carrier aircraft support process is proposed. This paper provides a reference to improve the carrier aircraft support capacity and aircraft carrier combat capacity.

***Keywords**: Carrier aircraft, Parallel closed-loop system, System Dynamics, Nimitz Surge Operations, evaluation method*

1. Introduction

With the rapid development of aircraft carrier in our country, the research on combat capability of aircraft carrier has become one of hot issues. Carrier aircraft is the main combat weapon of aircraft carrier. The sortie generation capacity of carrier aircraft is a major factor affecting aircraft carrier's combat capability. The key part of sortie generation capacity is the support capacity of carrier aircraft on the deck. Therefore, the research on support capacity is of great significance to improve the carrier aircraft support capacity and aircraft carrier combat capacity.

Carrier aircraft's support process has the following characteristics [1-4]. (1) Complexity: support process comprises a number of serial or parallel operations. (2) Delay: required personnel, resources and other supplies can not be put in place in time. (3) Closed-loop: operating network is closed-loop, because the number of carrier aircrafts is a constant. Therefore, the above characteristics are needed to take into account, when modeling support process.

At present, the methods used in modeling of support process include queuing theory [5, 6], Petri network method [7], Agent method [8, 9], Markov chain method [10, 11], *etc*. R. C. Jerkins described military launching and recovering systems using closed queuing networks and proposed a method of fork-join closed queuing network [12, 13]. Y. Hou used Petri network to establish launching process showing the status of carrier aircraft

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[14]. A. MacKenzie analyzed the carrier aircraft's dynamic real-time scheduling process using agent technology and obtained aircraft sortie rate [15, 16]. W. W, Fisher used Markov chain to model and analyzed logistics service system of weapon equipment [17]. The model can be directly used for analysis and evaluation of military logistics service's supply capacity. However, previous methods have failed to consider both dynamic process and static performance of support process. The calculations of previous methods are very large when a system has a lot of state variables. Therefore, a new method is needed to describe support process with complexity, delay and closed-loop.

System Dynamics method (SD) is suitable for analysis of systems with complex, dynamic and changeable characteristics. System Dynamics method has been applied to the analysis of the main factors successfully in the field of industrial development [18-22]. A. A. Ghobbar proposed a demand model for aircraft spare parts [23]. The factors affecting aircraft intact rate were analyzed. X. J. Wei used SD to model the communication equipment system [24-26]. The modeling feasibility using SD was proved. However, the previous researches focused on the complexity and delay of system. Few literatures considered the parallel and closed-loop of system. Therefore, there is a further need for realization of parallel closed-loop system with SD.

This paper establishes the carrier aircraft support process model based on System Dynamics. This model considers the parallel, complexity, delay and closed-loop characteristics of carrier aircraft support process. The dynamic and static performances of a system with parallel are analyzed. The main factors affecting carrier aircraft support capability are achieved through simulation and analysis

2. States Analysis for Support Process of Carrier Aircraft

2.1. Description of the problem

The relationships between relevant elements are complicated due to complexity, delay and closed-loop characteristics of carrier aircraft support process. The dynamic process is analyzed in the overall perspective.

2.2. Causality Diagram of Support Process

The states of different operations can be obtained through the analysis for feedback relationships between various factors in support process. Specially, the weapons loading operation performs in parallel with fueling operation. There are delays in weapons loading, fueling and other operations. The support process of carrier aircraft is illustrated in Figure 1.

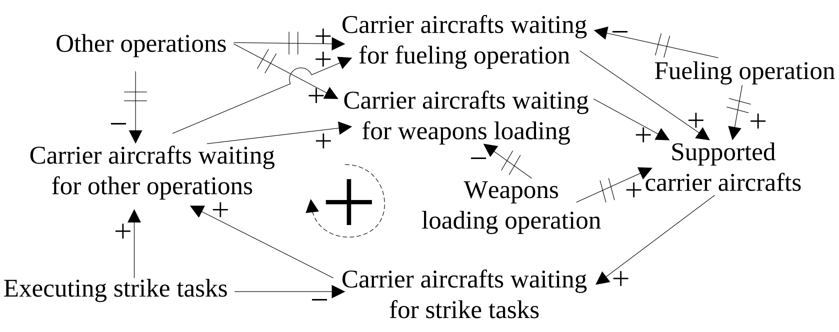

Figure 1. Causality Diagram of Support Process

Figure 1 shows a closed-loop feedback for support process of carrier aircraft.

(1) Chaining, chocking, filling tires with nitrogen and other operations are performed at

the beginning of support process. The following operations are weapons loading and fueling. The number of carrier aircrafts waiting for weapons loading and fueling will increase. The number of carrier aircrafts in other operations will decrease.

(2) The decreasing number of carrier aircrafts in weapons loading and fueling and increasing number of supported carrier aircrafts are achieved, when the weapons loading and fueling operations are finished.

(3) The supported carrier aircrafts are ready for executing strike tasks, when there is a demand for strike.

(4) The number of carrier aircrafts waiting for other operations will increase and number of carrier aircrafts in executing strike tasks will decrease, after the strike tasks are completed.

The numbers of carrier aircrafts in different operations will tend to unchangeable in conditions of the limited support capacity of carrier aircraft.

3. Modeling for Support Process of Carrier Aircraft Based on System Dynamics

3.1. Relationship Flow Diagram for Support Process of Carrier Aircraft

The relationship flow diagram will reveal the system structure of support process more clearly than causality diagram. The flow diagram is established according to the causality diagram, as shown in Figure 2.

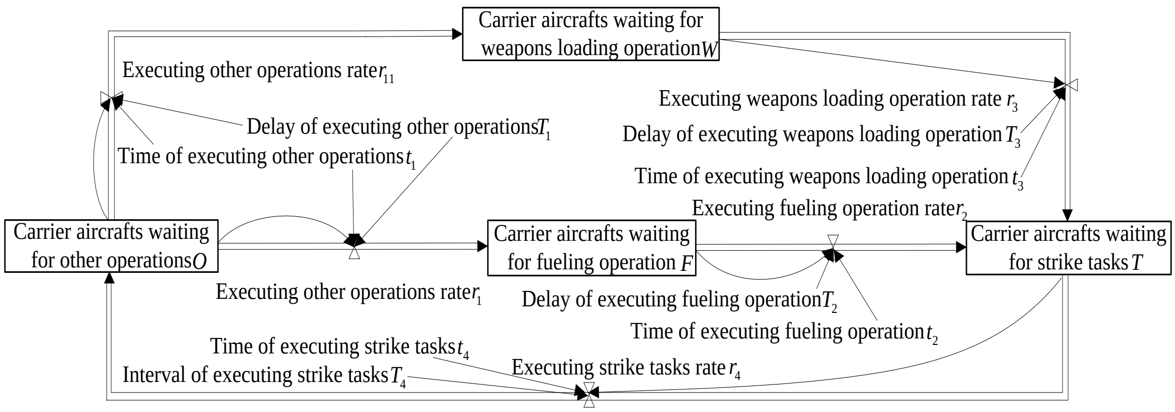

Figure 2. Relationship Flow Diagram of Support Process

In Figure 2, the box denotes the accumulated state variable. The double cable denotes the changes of state variable, such as the inflow rate and outflow rate. The arc represents quantitative and logical relationship of variables. The state variables and rate variables are analyzed in Figure 2.

The following assumptions should be considered when modeling the flow diagram of support process.

(1) The support process of carrier aircraft is a closed-loop system. There is a certain number of carrier aircrafts waiting for other operations at the beginning.

(2) The personnel and resources may not be supplied in time. Therefore, there are delays in weapons loading, fueling and other operations.

(3) The strike tasks are executed as scheduled, and hence there is a certain interval between two strike tasks.

(4) The weapons loading and fueling operations are performed in parallel. The number of carrier aircrafts is considered to be doubled before weapons loading and fueling in order to guarantee that the total number of carrier aircrafts in the closed-loop system is

fixed. A carrier aircraft can perform the next operation, after the weapons loading and fueling operations are both finished. Therefore, the minimum value between the numbers of weapons loaded and fueled carrier aircrafts can be passed to the next operation.

3.2. Analysis of Structural Equations for Support Process

Figure 2 describes causal relationship and the system structure of the elements. However, the quantitative relationship between the variables can not be presented in Figure 2. The structural equations are shown for the analysis of static performance.

In Figure 2, the inflow rate of the carrier aircrafts waiting for other operations O is the executing strike tasks rate r_4. The outflow rate is the executing other operations rate r_1. The state equation of the carrier aircrafts waiting for other operations O is expressed in Equation (1).

$$O(t)=O(t-\Delta t)+\left[2r_4(t-\Delta t)-r_1(t-\Delta t)-r_{11}(t-\Delta t)\right]\cdot\Delta t \tag{1}$$

Similarly, the state equation of the carrier aircrafts waiting for fueling operation F is expressed:

$$F(t)=F(t-\Delta t)+\left[r_1(t-\Delta t)-r_2(t-\Delta t)\right]\cdot\Delta t \tag{2}$$

The state equation of the carrier aircrafts waiting for weapons loading operation W is expressed:

$$W(t)=W(t-\Delta t)+\left[r_{11}(t-\Delta t)-r_3(t-\Delta t)\right]\cdot\Delta t \tag{3}$$

The state equation of the carrier aircrafts waiting for strike tasks T is expressed:

$$T(t)=T(t-\Delta t)+\left[MIN\left(r_2(t-\Delta t),r_3(t-\Delta t)\right)-r_4(t-\Delta t)\right]\cdot\Delta t \tag{4}$$

The following equations can be obtained, according to the rate variables' cumulative effects on the state variables.

The rate equations of executing other operations rates r_1 and r_{11} is expressed:

$$r_1(t)=r_{11}(t)=O(t)/(T_1+t_1) \tag{5}$$

The rate equation of executing fueling operations rate r_2 is expressed:

$$r_2(t)=F(t)/(T_2+t_2) \tag{6}$$

The rate equation of executing weapons loading operations rate r_3 is expressed:

$$r_3(t)=W(t)/(T_3+t_3) \tag{7}$$

The rate equation of executing strike tasks rate r_4 is expressed:

$$r_4(t)=T(t)/(T_4+t_4) \tag{8}$$

The carrier aircrafts waiting for other operations O is expressed with the rate variables, according to Equation (1) and (5).

$$O(t)=r_1(t-\Delta t)\cdot(T_1+t_1-2\Delta t)+2r_4(t-\Delta t)\cdot\Delta t \tag{9}$$

The carrier aircrafts waiting for fueling operation F is expressed with the rate variables, according to Equation (2) and (6).

$$F(t)=r_2(t-\Delta t)\cdot(T_2+t_2-\Delta t)+r_1(t-\Delta t)\cdot\Delta t \tag{10}$$

The carrier aircrafts waiting for weapons loading operation W is expressed with the rate variables, according to Equation (3) and (7).

$$W(t)=r_3(t-\Delta t)\cdot(T_3+t_3-\Delta t)+r_{11}(t-\Delta t)\cdot\Delta t \tag{11}$$

The carrier aircrafts waiting for strike tasks T is expressed with the rate variables, according to Equation (4) and (8).

$$T(t)=r_4(t-\Delta t)\cdot(T_4+t_4-\Delta t)+MIN\left(r_2(t-\Delta t),r_3(t-\Delta t)\right)\cdot\Delta t \tag{12}$$

The following conclusions can be obtained from Figure 2. The effect of executing strike tasks rate is to increase the number of carrier aircrafts waiting for other operations and to decrease the number of carrier aircrafts executing strike tasks. The effect of executing other operations rate is to increase the number of carrier aircrafts waiting for weapons loading and fueling operation and to decrease the number of carrier aircrafts executing other operations. The effect of executing fueling operation rate is to increase the number of carrier aircrafts waiting for strike tasks and to decrease the number of carrier aircrafts executing fueling operation. The effect of executing weapons loading operation rate is to increase the number of carrier aircrafts waiting for strike tasks and to decrease the number of carrier aircrafts executing weapons loading operation.

The number of supported carrier aircrafts will increase through the effects of weapons loading, fueling and other operations, according to the above analysis of dynamic process. Therefore, the support process is a positive feedback system with differential regulation.

3.3. Analysis for Support Capability of Carrier Aircraft

The supported carrier aircrafts S are the carrier aircrafts with the completion of weapons loading, fueling and other operations. The state equation of supported carrier aircrafts S is expressed:

$$S(t)=r_4(t-\Delta t)\cdot(T_4+t_4-\Delta t)+MIN\left(r_2(t-\Delta t),r_3(t-\Delta t)\right)\cdot\Delta t \tag{13}$$

The definition of support capability SC is the proportion of the number of supported carrier aircrafts in the total number of carrier aircrafts. The expression of support capacity SC is as shown in Equation (14).

$$SC(t)=S(t)/O(0)\times 100\%=\left[r_4(t-\Delta t)\cdot(T_4+t_4-\Delta t)+MIN\left(r_2(t-\Delta t),r_3(t-\Delta t)\right)\cdot\Delta t\right]/O(0)\times 100\% \tag{14}$$

The tree structure diagram of factors affecting the number of supported carrier aircrafts is as shown in Figure 3.

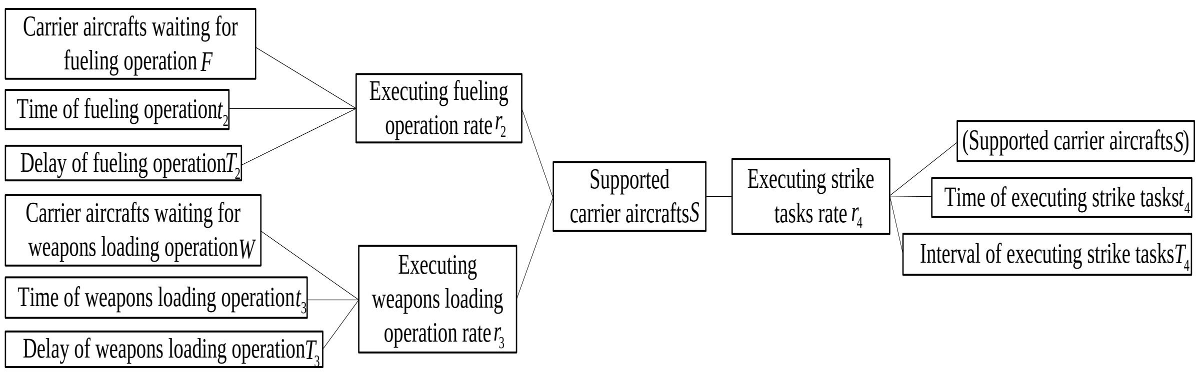

Figure 3. Tree Structure Diagram of the Number of Carrier Aircraft to Ensure the Completion of the Protection

The factors affecting the number of supported carrier aircrafts include the executing fueling operation rate, the executing weapons loading operation rate and the executing strike tasks rate, according to Equation (13) and Figure 3. There is a feedback loop in Figure 3. The executing strike tasks rate is affected by the number of supported carrier aircrafts.

4. Simulation and Analysis of Dynamic Process and Static Performance

4.1. Parameter Settings for Simulation

This paper takes the support process of "Nimitz" carrier aircraft [1] as the object of analysis. The related parameters of support process are shown in Table 1.

Table 1. Parameters of Support Process

Parameter	Value	Parameter	Value
Number of carrier aircrafts	68	Time of executing weapons loading operation	8 min
Time of executing other operations	15 min	Delay of executing weapons loading operation	6 min
Delay of executing other operations	1 min	Time of executing strike tasks	55 min
Time of executing fueling operation	15 min	Interval of executing strike tasks	60 min
Delay of executing fueling operation	8 min		
Number of carrier aircrafts	68	Time of executing weapons loading operation	8 min
Time of executing other operations	15 min	Delay of executing weapons loading operation	6 min
Delay of executing other operations	1 min	Time of executing strike tasks	55 min
Time of executing fueling operation	15 min	Interval of executing strike tasks	60 min
Delay of executing fueling operation	8 min		

The number of carrier aircrafts waiting for other operations is 68 in the initial state. The numbers of carrier aircrafts waiting for weapons loading, fueling and strike tasks are 0. The total time of simulation is 100 hours. The simulation step is 0.9375 min.

4.2. Analysis for Dynamic Process of Support Process

The factors affecting support capacity is analyzed through changing the parameters of weapons loading, fueling and other operations. The way to improve support capacity of carrier aircraft is achieved.

(1) The influence of other operations

The other operations capacity is affected by its time and delay. The sum of its time and delay is adjusted by 20% increased, 10% increased, 10% decreased and 20% decreased. The dynamic process of support process is shown in Figure 4 and Figure 5.

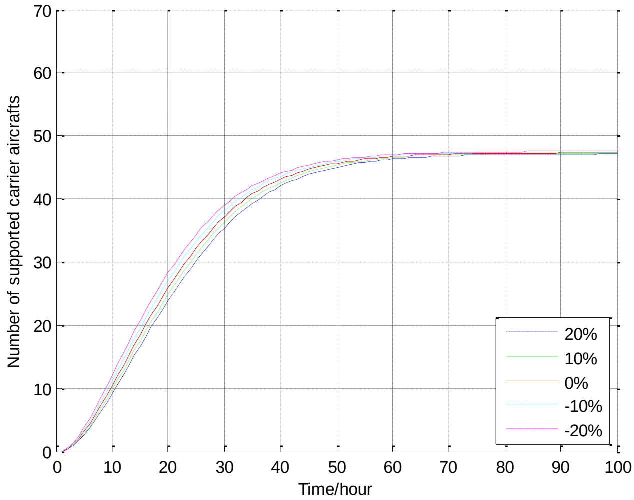

Figure 4. The Other Operations Influence on the Number of Supported Carrier Aircrafts

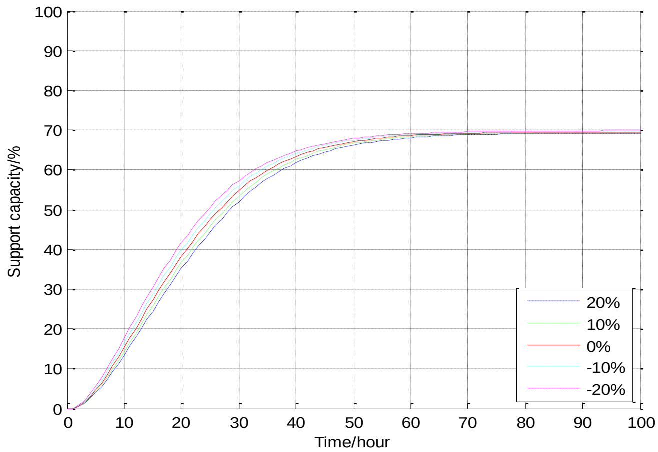

Figure 5. The Other Operations Influence on the Support Capacity

The number of supported carrier aircrafts S and support capacity SC are increased with the reduction of the time and delay in executing other operations before about 80th hour in Figure 4 and Figure 5. The number of supported carrier aircrafts and support capacity are intend to steady after about 80th hour. The other operation influence on the dynamic process is greater than that on static process.

(2) The influence of weapons loading and fueling operations

The weapons loading operation is executing in parallel with fueling operation. Therefore, one of weapons loading and fueling operations parameters will affect the support capacity with the limit of the other operation parameters. The sum of their time and delay is adjusted by 20% increased, 10% increased, 10% decreased and 20% decreased. The dynamic process of support process is shown in Figure 6 and Figure 7.

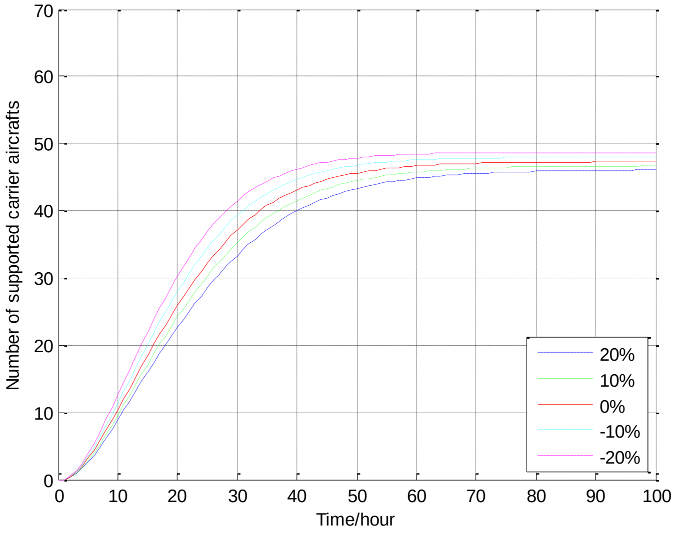

Figure 6. The Weapons Loading and Fueling Operations Influence on the Number of Supported Carrier Aircrafts

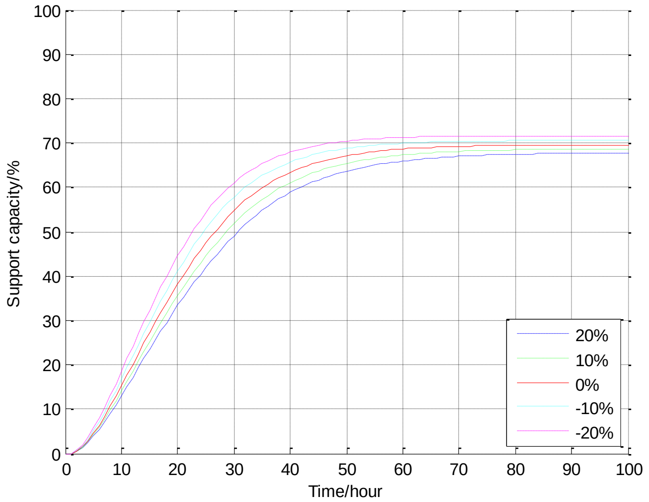

Figure 7. The Weapons Loading and Fueling Operations Influence on Support Capacity

(3) The influence of strike tasks

Similarly, the sum of strike tasks' time and interval is adjusted by 20% increased, 10% increased, 10% decreased and 20% decreased. The dynamic process of support process is shown in Figure 8 and Figure 9.

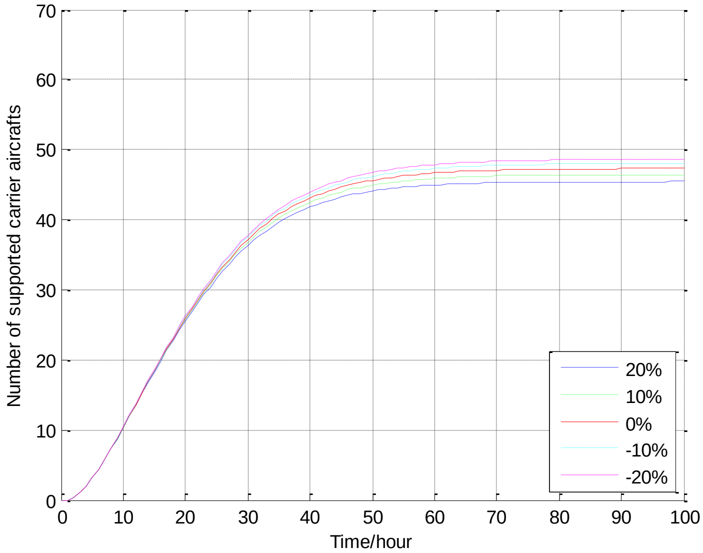

Figure 8. The Strike Tasks Influence on the Number of Supported Carrier Aircrafts

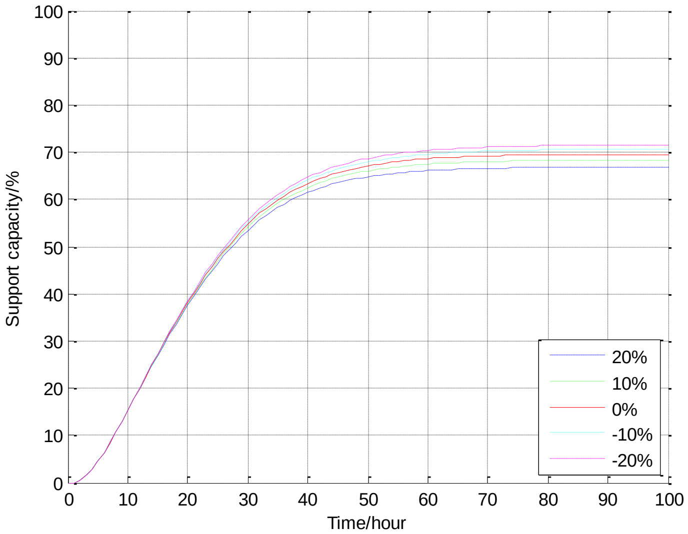

Figure 9. The Strike Tasks Influence on Support Capacity

The number of supported carrier aircrafts S and support capacity SC are increased with the reduction of the time and delay in executing weapons loading and fueling operations before about 80th hour in Figure 8 and Figure 9. The number of supported carrier aircrafts and support capacity are intend to steady after about 80th hour. The weapons loading and fueling operation influence on the dynamic process is greater than that on static process.

The number of supported carrier aircrafts S and support capacity SC are increased with the reduction of the time and interval in executing strike tasks before about 80th hour in Figure 8 and Figure 9. The number of supported carrier aircrafts and support capacity are intend to steady after about 80th hour. The strike tasks influence on the static process is greater than that on dynamic process.

4.3. Analysis for Static Performance of Support Process

The every factor's influence on support capacity is collected and analyzed according to Figure 4-9, when the support process becomes steady. The change rate of support capacity is defined as the proportion of support capacity rate in factor rate. The results are shown in Table 2, 3 and 4.

Table 2. Comparison of Other Operations Influence

Change rate of time and delay in other operations	Support capacity	Change rate of support capacity
-20%	69.9197%	-0.0243
-10%	69.7482%	-0.0240
0	69.5812%	0
10%	69.4157%	-0.0238
20%	69.2501%	-0.0238

Table 3. Comparison of Weapons Loading and Fueling Operations Influence

Change rate of time and delay in weapons loading and fueling operations	Support capacity	Change rate of support capacity
-20%	71.5847%	-0.1440
-10%	70.5460%	-0.1387
0	69.5812%	0
10%	68.6751%	-0.1302
20%	67.8140%	-0.1207

Table 4. Comparison of Strike Tasks Influence

Change rate of time and interval in strike tasks	Support capacity	Change rate of support capacity
-20%	71.5410%	-0.1408
-10%	70.6369%	-0.1517
0	69.5812%	0
10%	68.3322%	-0.1795
20%	66.8315%	-0.1976

The support capacity increases in proportion as the factor decreases from Table 2, 3 and 4.The other operations influence on support capacity is the least. Its change rate of support capacity is -0.0240. The weapons loading and fueling operations influence on support capacity is similar with the strike tasks influence on support capacity, and their change rates of support capacity are -0.1350 and -0.1674 respectively. Therefore, the bottleneck factors affecting support capacity are the weapons loading operation, fueling operation and strike tasks in the static performance analysis.

The influence of various factors on the support capability is analyzed, through the simulation for the dynamic and static performances of the support system.

(1) The other operations mainly affect the dynamic process and have little influence on the static performance of support process.

(2) The weapons loading and fueling operations have great influence on both the dynamic process and the static performance.

(3) The strike tasks have a great impact on the static performance and little effect on the dynamic process.

Therefore, the bottleneck factors affecting support capacity are the weapons loading and fueling operations in the dynamic process and static performance. The reduction of the time and in delay weapons loading and fueling operations contributes to the improvement of the carrier aircraft support capacity and aircraft carrier combat capacity.

5. Conclusion

A modeling method for parallel closed-loop support process is proposed based on System Dynamics. The modeling problems of parallel operations and the fixed number of carrier aircraft in closed-loop system are solved in this paper. The flow diagram and state equations are established for support process. Support capacity is defined. The bottleneck factors affecting support capacity are the weapons loading and fueling operations through the analysis of the dynamic process and static performance. This paper provides a reference to improve the carrier aircraft support capacity and aircraft carrier combat capacity. The parallel operations modeling method proposed in this paper can be applied to the general supply chains, which provide a new solution for the research on the closed-loop supply chains with parallel operations.

Acknowledgments

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Conflicts of Interest

The authors declare no conflict of interest.

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