Availability of Weapon Systems with Air-attack Missions

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During air-attack operations, i.e., air-to-air and land-air operations in battles, maintaining a high level of availability of weapon systems (aircraft and weapons) becomes important from the point of view of winning the battle. Availability may depend on severity of combat operations, attrition factors (battle damage failures and reliability related failures), and logistic delays in weapons deployment and in the repair process. In this paper, a simulation model is developed for availability of weapon systems considering air-to-air and land-air combat operations, multiple failures causing aircraft failure and logistic delays in weapons deployment, and in the repair process. The availability of aircraft and the availability of weapons are separately derived from simulation and the product of them is denoted as combined availability for analysis. The results are analyzed in terms of fluctuations in availability on specified days of battle such as 1, 7, 14, and 21 days from the graphical output.

The simulation procedure employs discrete event simulation technique using Monte Carlo methods. The time to failure distribution and the time to repair distribution for the major subsystems of the aircraft and helicopters is considered to be Weibull and exponential respectively. The logistic delay time distribution for weapons replenishment and for logistic factors, spares, crew, and equipment, is considered to be lognormal.

Assuming a certain range of values for air-attack missions and for the number of sorties to be generated and a set of reliability and maintainability parameters for the considered major subsystems of the aircraft, the simulation for availability is analyzed. The number of aircraft (both fixed wing and rotary wing) for different missions is varied. The possible reduction in availability due to changes in logistic factors, considering two extreme cases noted as optimistic and pessimistic is specifically examined through simulation runs. The results obtained indicate the pronounced decrease in availability of weapon systems and their fluctuations due to multiple failures and logistic delays in weapons replenishment and in the repair process. The results are, however, highly sensitive to a combination of reliability, maintainability, and logistic delay parameters.

Key Words: Discrete event simulation, Monte Carlo technique, weapon systems, availability, military simulation

1. Introduction

Availability of weapon systems (i.e., weapon platform and the weapons) during combat operations is essential from the point of view of outcome of the battle. During campaigns, maintaining a high level of availability of weapon systems becomes difficult. The availability of the weapon platforms decreases to a low level within the first few days of the battle [1,2,3]. This is mainly due to logistic delays affecting the repair process and attrition factors such as battle damage failures and reliability related failures. The failures have been either single or multiple since many subsystems of the aircraft were considered.

The campaign in air-attack missions consists of combat operations, i.e., air-to-air and land-air operations, which are usually planned in advance. The air-to-air operations are likely to be in the initial days of the battle. After the targets are softened, the land-air operations begin. These air operations consist of several types of missions. Two important missions in air-to-air operations are counter-air (CA) and ground attack (GA) (air to ground) missions. Under land-air operations the important missions considered are battle area interdiction (BAI) and close air support (CAS) missions (mainly to provide support for army movement). Though there are other combat missions in practice, such as surveillance, reconnaissance, escort, and battle damage assessment, we do not consider them separately. We assume that these are part of the important missions we consider.

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During the first few days of the battle, we consider air-to-air operations and then onwards, land-air operations are considered though there could be a few air-to-air operations. The number of missions and the number of sorties to be generated in a mission on a particular day depend on the number and type of targets to be attacked on that day. To this end, we consider both the number of missions and the number of sorties to vary randomly over an interval.

The types of aircraft for different mission types vary in general. Though multi-role aircraft can be used for any type of mission, it will be limited in number. We consider only the number of aircraft for different mission types to be distinct. Further, the number of aircraft considered for ground attack and battle area interdiction mission will be considered together. For close air support missions, the ratio of the number of fixed wing and rotary wing aircraft (helicopters) considered for sortie generation is 1:2.

In a study of battle tanks, Kessler has analyzed the loss rate due to battle damage of tanks and the maintenance requirements in wartime through a simulation to arrive at logistic requirements using exponential distribution [4]. Emerson has discussed the capability of airbases to generate effective combat sorties and some improvement options, which could increase the combat capability of airbases during wartime [5]. In an earlier paper, Emerson has developed a model for assessing the airbase damage during battles [6]. For an engineering system, Castro and Cavalca have considered optimizing the availability using genetic algorithm [7]. Fisher et al., have provided an overview for the composite logistics model [8]. In our earlier papers we developed simulation models for availability of weapon systems under battlefield conditions considering single failures, multiple failures, and logistic delays affecting the repair process. In [1], the weapon system as a whole (i.e., the aircraft as an entity) was considered for failure. In [2], the different subsystems of the aircraft were considered. The repair process with logistic delay as an entity was considered at three repair levels, i.e., base level, intermediate level and the depot level. In [3], we considered multiple failures of the subsystems of the aircraft and the logistic delay were modeled in detail for the delay due to spares, crew, and equipment.

The simulation model developed here considers the fighter aircraft as the weapon platform. The failure of the aircraft may be due to failure of one or more of its subsystems. In a survey article, Cooley has analyzed failure of different subsystems and components in aircraft mishaps [9]. From the data on South Asia War, we found that the subsystems (structures, flight control, propulsion, fuel system, power system, avionics, crew station, and armament fitments) caused the aircraft failure [10]. Therefore, in the present simulation, we have considered the failure for these subsystems. For the helicopters, the major subsystems considered for failure are helicopter main rotor, helicopter engine, and the tail rotor.

In severe combat missions one or more of the subsystems of the aircraft/helicopter fail due to battle damage or system unreliability. This can be because of a single common cause failure or can occur independently. Such multiple failures may cause catastrophic events, like total loss of the aircraft. The assumption made here is that that when battle damage failure occurs, the total loss of the aircraft is considered if the subsystems (propulsion and fuel system or structures, flight control or structures, crew station, and avionics) fail at once. In other cases, the failed subsystems may be repaired in order to restore the aircraft to working condition. The repair work may be performed at the field or at nearby base repair depots. The repair work may, however, require logistic support in terms of logistic factors: spares, crew, or equipment. Since we assume that the battle begins with near full repair capabilities, during the first few days of the battle the need for logistic supply may not arise. More and more aircraft/helicopter would fail as the intensity of the battle increases. This may lead to inadequacy in logistics supply. This need can be met from another source such as nearby depots. In order to reflect delay in repair due to lack of logistic factors (spares, crew, or equipment) at the repair level the logistic delay is considered in the simulation.

The weapons that are used in air-attack operations are bombs, missiles, and rockets. The type (bombs, missiles, and rockets) and amount (in terms of weight) to be used in a mission depends on the targets to be attacked and the extent of damage to be caused for the target. In the simulation, we computed the tons of weapons to be used in a mission, which is considered to be uniformly distributed over a range. The weapons planned to be used may have to be transported from a nearby location if stored in advance. Otherwise, it has to be brought from some other source. Therefore, logistic delay is involved in both the cases. Toward this end, a logistic delay term is considered in weapons replenishment. Further, the amount of weapons required may not always be possible to meet due to various reasons. Therefore, the amount of weapons to be supplied is made random.

2. Simulation Methodology

The simulation methodology is based on discrete event simulation (DES) using Monte Carlo method [11]. The air-to-air operations are considered to be severe for the first four days of the battle. The counter-air and ground attack missions are considered under air-to-air operations. From the 5th day of the battle, land-air operations are considered with a few air-to-air operations. The battle area interdiction and close-air-support missions are included under land-air operations. Since it is difficult to predict the number of missions and the number of sorties to be generated in a mission on a particular day, we consider them to be distributed according to a uniform distribution in some specified interval. The limits of the interval will be the expected minimum number of missions or sorties to be generated and the maximum number of missions or sorties.

As the aircraft subsystems (structures, propulsion, fuel system, power system, crew station, and armament fitments) are mechanical in nature, failure rates are treated as age related. Kececioglu has analyzed the reliability of mechanical systems and components [12]. Therefore, Weibull distribution is considered appropriate for the time-to-failure distribution. Boe and Tveit have used Weibull distribution to fit the marine steam boiler failure data for naval ships [13]. For flight control subsystem, the Weibull distribution is employed as the failure time distribution as it often includes mechanical components. Avionics consists basically of electronic components; therefore exponential distribution for failure time may be considered. The helicopter main rotor, helicopter engine, and the tail rotor are mechanical in nature. Hence the Weibull distribution for the failure times of these subsystems has been used.

The repair process may follow either exponential distribution or lognormal distribution; in the present paper we consider only exponential distribution for the repair process. Crocker and Kumar have provided a case study by comparing the age-related maintenance and the reliability centered maintenance [14]. The logistic delay times due to logistic factors (spares, crew, equipment, and logistic delay time) due to weapons replenishment are modeled separately as lognormal [15,16].

The probability distributions and the reliability functions of these distributions are as follows:

Exponential distribution:

Probability distribution:

$$f(t) = \lambda \exp(-\lambda t), \quad t > 0, \lambda > 0 \qquad (1)$$

Reliability function:

$$R(t) = \exp(-\lambda t) \qquad (2)$$

where λ is the parameter of interest and the mean of the distribution is 1/λ.

Weibull distribution:

Probability distribution:

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \quad t > 0, \eta, \beta > 0 \qquad (3)$$

Reliability distribution:

$$R(t) = \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \qquad (4)$$

where β is the shape parameter and η is the scale parameter or characteristic life.

Lognormal distribution:

Probability distribution:

$$f(t) = \frac{1}{t\sigma_{ln}\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{\log(t)-\mu_{ln}}{\sigma_{ln}}\right)^{2}\right), \qquad (5)$$

$$t \geq 0, \quad -\infty < \mu_{ln} < \infty \quad \sigma_{ln}^{2} > 0 \quad \sigma_{ln}^{2} > 0$$

where μ_{1n} and σ_{1n} are the mean and standard deviation of the normally distributed random variable log(*t*) (for lognormal distribution the reliability function cannot be expressed as a closed form expression).

Most of the studies consider only two states, with the states being failure and repair. It could be noted that if the time to failure and time to repair distributions are modeled as exponential, analytical expression for availability can be easily derived. This is possible because the failure and repair process will then be Markov. If any of these distributions are not exponential, the resulting stochastic process will be non-Markov. In this case, deriving analytical expression for the availability becomes difficult [17]. Toward this end, a simulation technique is most appropriate for estimating the availability.

The important assumptions of the simulation model developed here are as follows:

1. Battle damage and unreliability are considered possible causes of failure of aircraft/helicopter.
2. There can be single or multiple failures of the subsystems of the aircraft/helicopter.
3. Simultaneous repair is considered for all the failed subsystems.
4. The logistic requirement in terms of the logistic factor: (spares, crew, and equipment is met simultaneously).
5. The weapons request is done only at the end of the day
6. The weight in terms of tonage of weapons considered available on the first day is assumed to be 2.5 times the initial requirement.
7. On any day, except on the first day, the expected requirement in terms of tons of weapons for use is taken to be 1.5 times the initial requirement
8. The logistic delay times are different for components (spares, crew, and equipment) of aircraft repair and for weapons replenishment.

The simulation model is developed as follows:

1. The number of missions on any day is uniformly distributed over a specified interval.
2. The number of sorties to be generated in a mission is uniformly distributed over a specified interval.
3. Weibull distribution with parameter set (β_i^a, η_i^a) , i =1, 2, …, 8 is considered as the time to failure distribution due to system unreliability for the subsystems of the aircraft. For the subsystems of the helicopters Weibull

distribution also is considered with the parameter set being (β_i^h, η_i^h), i = 1, 2, 3.

4. A discrete probability distribution with probability mass, p_i^a i = 1, 2, …, 8 is considered as the battle damage probability distribution for aircraft with p_i^a as the probability of battle damage for the ith subsystem of aircraft and $\sum p_i^a = 1$. Similarly, for the subsystems of helicopter, the corresponding probabilities are p_i^h i = 1, 2, 3 with $\sum p_i^h = 1$for helicopters.
5. For all the subsystems, the distribution for time to repair is exponential with parameter μ . The mean time to repair (*MTTR*) is $1/\mu$. For aircraft subsystems, the parameter is denoted as μ_i^a and the MTTR is denoted as $MTTR_i^a$, i = 1, 2, …, 8, and for helicopter subsystems it is μ_i^h and $MTTR_i^h$, i = 1, 2, 3.
6. The logistic requirement probability is q_s for spares, q_c for crew, and q_e for equipment, such that $q_s + q_c + q_e = 1$.
7. The logistic delay time distribution for spares, crew and equipment is modeled as lognormal with the parameter set being $({}^{s}\mu_{1n}, {}^{s}\sigma^2_{1n})$ for spares, $({}^{c}\mu_{1n}, {}^{c}\sigma^2_{1n})$ for crew and $({}^{e}\mu_{1n}, {}^{e}\sigma^2_{1n})$ for equipment. M_{80} and M_{50}, i.e., the 80th and 50th percentiles of the distribution are used to derive these parameters.
8. The weapons requirement in terms of weight of weapons in any mission is assumed to be uniform over a specified interval.
9. The logistic delay time distribution for supply of weapons is modeled as lognormal with the parameter set being $({}^{wp}\mu_{1n}, {}^{wp}\sigma^2_{1n})$

The inverse transform method is used to generate the random variates from the exponential and the Weibull distributions [18]. The transformation due to Marsaglia and Bray is used to generate random variates for the normal distribution and hence for the lognormal distribution [19].

3. Simulation Structure

The state transition diagram given in Figure 1 is used to explain the simulation structure. The transition states are named as "aircraft/helicopter in service," "aircraft/helicopter under repair," "aircraft/helicopter attrited," "weapons," and "logistics." The reliability related failures and the battle damage failures are the two possible transitions that take place from the "aircraft/helicopter in service" state to the "aircraft/helicopter in repair" state. The logistic support in terms of spares, crew, or equipment may be required at the repair state. Therefore, a transition is shown from the "logistics" state to the "aircraft/helicopter in repair" state, which would represent the aircraft/helicopter requiring logistics support. A transition state, "aircraft/helicopter attrited," is considered, which caters for the transition from the "aircraft/helicopter in service" state to the "aircraft/helicopter attrited" state. This is possible because of our assumption that when damage failure occurs, if the aircraft subsystems failed are structures and flight control or structures, crew station and avionics, or propulsion and fuel system, then the aircraft is considered as attrited and in the case of helicopters, if all the subsystems considered are failed, then the helicopter is considered as attrited. The weapons requirement for aircraft/helicopter is considered to be a separate state having transition with only the "aircraft/helicopter in service" state.

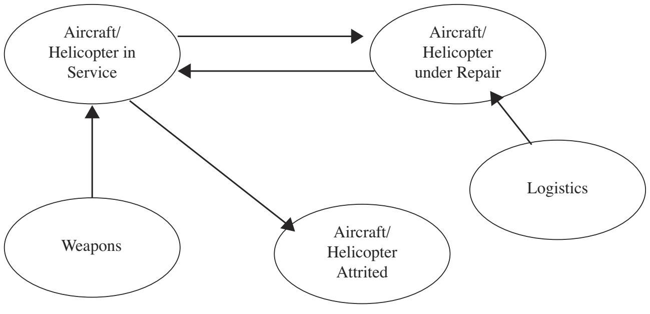


Figure 1. State transition diagram for simulation

4. Simulation Implementation

The simulation is implemented with a certain number of fighter aircraft and helicopters for different types of missions with the assumption that all of them are in-service condition on the first day. For the first four days we consider only counter-air and ground attack missions. From 5th day to the end of 2nd week, few counter-air and ground attack missions are considered. The land-air operations (the battle area interdiction and close air support missions) are considered from 5th day until the end of simulation (extending to 4 weeks). This pattern can be varied during simulation runs. The number of missions on a given day is simulated from the considered uniform distribution. For each mission, the amount of weapons in terms of weight of weapons to be carried is simulated randomly from the considered uniform distribution. If the number simulated is greater than the available weight of weapons, it will be rejected and a fresh random number is simulated. The number of sorties in each mission is again randomly generated. The number simulated should lie within the available number of aircraft, otherwise the simulation run is repeated.

For close air support missions, the number of aircraft and helicopters is considered in the ratio 1:2, for achieving the number of sorties simulated. The aircraft requirement is met from the number of ground attack aircraft/helicopter considered. For illustrative purpose, the sortie duration (flying hours) is taken to be 3 hours and the simulation interval is taken as 1 day, (i.e., 24 calendar hours). The number of aircraft, number of sorties per mission and sortie duration can be varied in any simulation run. The mission start time is randomly generated on each day so that the planned missions are performed on that day, keeping in mind the sortie duration.

The battle damage rate is considered to decrease with the number of days. This rate of decrease is implemented as user input in the simulation.

For each sortie, using simulation runs, we evaluate the possibility of battle damage failures and reliability related failures. The simulation implements the aircraft/helicopter failure when one or more of the subsystems of the aircraft/helicopter fail. For considering the failure due to battle damage, a uniform random variate, ν_1, is generated and is compared with the battle damage rate assumed for that particular day. The battle damage failure is considered to have occurred if ν_1 turns out to be less than the battle damage rate for that day. To find out the number of subsystems failed, say n_a $(1 \leq n_a \leq 8)$for aircraft, and n_h $(1 \leq n_h \leq 3)$ for helicopters, a uniform random variate, ν_2, is generated. This is accomplished using random sampling without replacement and the battle damage probabilities p^a_i, i = 1, 2, ... 8 for aircraft, and p^h_i, i = 1,2,3 for helicopters. If n_a or n_h is greater than 1, then we need to look for the set of different subsystems failed to consider whether the aircraft/helicopter has been attrited. In case of aircraft, if the failed set contains the subsystems (structures and flight control or structures, crew station and avionics or propulsion, and fuel system) the aircraft is considered as attrited. In case of helicopters, if the failed set contains all three subsystems, then it is considered as attrited. If the aircraft/helicopter is attrited, it is subtracted from the available number of aircraft/helicopter for all the days. If the aircraft/helicopter is not attrited, the failed subsystems are noted.

We proceed to find out the reliability related failures for those which have not failed due to battle damage. To do this, we first evaluate the reliability of those subsystems by considering the time elapsed, since previous overhaul or preventive maintenance actions as the age (τ) of those subsystems. The preventive maintenance (PM), or overhauling, is carried out at time intervals denoted T, the Time Between Overhaul (TBO) is assumed. In practice, overhauling is done for propulsion and fuel system; for other subsystems preventive maintenance and inspection is carried out. For the sake of simplicity, a single terminology TBO is used. We simulate the time elapsed from the previous overhaul, or preventive maintenance action, by generating a random number in the interval (0,T). This is generated only once for all the subsystems of all aircraft/helicopter considered on the first day prior to the start of the simulation and this is taken as the age τ of the subsystems on the first day before flying. The sortie duration of 3 hours is added to τ after each sortie for subsequent reliability calculations. We simulate the reliability related failed subsystems using a uniform random number ν_3. This is accomplished by comparing ν_3 with the unreliability of those subsystems that did not fail due to battle damage. If the unreliability of a particular subsystem is greater than ν_2 , then particular subsystem is considered to have failed. The subsystems failed are noted in that manner.

The repair times for the failed subsystems are simulated using the corresponding exponential distribution. The repair work assumed for all the failed subsystems is done simultaneously. Therefore, the actual repair time is taken as the maximum of the repair times simulated.

As the battle begins with near-full base capabilities, it is assumed that during the first 2 days of the battle, there will be no logistic delay in terms of logistic factors (spares, crew, or equipment) for the repair process. This restriction can always be varied. From 3rd day on, we simulate the logistic requirement using the logistic requirement model. Toward this end, a uniform random number ν_4 is generated to find out whether any one or two or all the three logistic factors (i.e., spares, crew, and equipment) are required, say n_{ls} $(0 \leq n_{ls} \leq 3)$. Then, from random sampling without replacement, the n_{ls} types of logistic requirements are obtained using the probabilities: $q_s = 0.5$ for spares, $q_c = 0.3$ for crew, and $q_e = 0.2$ for equipment. Depending on the battlefield situation, the logistic requirement probabilities can be varied. The logistic delay times are then simulated using the corresponding lognormal distribution. Because of our assumption that all the logistic requirement factors are met simultaneously, the actual logistic delay time is taken as the maximum of the logistic delay times simulated. The actual repair time is obtained by adding the logistic delay time.

The decision on the number of aircraft available at the end of the day is made on the basis that the aircraft has failed or not; and if failed, whether it is repaired and made available within that day (24 calendar hours). The use of 24 calendar hours can be modified by taking the simulation interval either as 12 hours or 8 hours as required. To accomplish this, we compare the actual repair time with the time available on that day since the time of failure. If the actual repair time exceeds the time available on that day, it is considered not available at the end of that day. Further, we check to find the day on which it becomes available and consider accordingly. By subtracting the number of aircraft not available at the end of the day form the number of aircraft available on that day, the number of available aircraft at the end of each day is obtained. The ratio of the number of aircraft available at the end of day to the initial number deployed for battle at the start of the simulation is taken as the availability of aircraft on that day.

The total weight of weapons available on the first day is assumed to be 2.5 times the initial requirement based on the planned missions. On any day we expect 1.5 times the initial weight of weapons to be available for use. The weapons requirement is calculated based on this assumption. The request for additional weapons is made only at the end of the day. This is done so as to make the weapon inventory to be 1.5 times the initial weight of weapons. The difference is obtained by subtracting the tons of weapons used on each day with the tons of weapons made available at the start of the simulation day. Due to various problems such as size, cost, location of storage, and weather conditions, it may not always be possible to replenish the requested amount of weapons. Therefore, we considered this amount to be random in the interval from zero to the requested tons of weapons. This is simulated whenever the request is made at the end of day. The logistic delay time is then simulated from the considered lognormal distribution. Since the mission planning may be done in advance, we consider that the simulated weight of weapons is available on the next day if the simulated lognormal variate is less than 16 hours otherwise it is considered to available on the next-to-next day. The availability of weapons is taken as the ratio of the difference obtained above to the tons of weapons available before the start of the simulation on that day.

The availability of the weapon systems is calculated as the product of the availability of the aircraft and the availability of the weapons.

$$A\ (\text{Weapon System}) = A\ (\text{Aircraft}) * A\ (\text{Weapons})$$

The software for the simulation runs is written in Turbo C.

5. Simulation Results

5.1 Parameter Values

It may be noted that because of the highly sensitive nature of the subject, not much data are available in open literature. Also, the authors did not have access to other historical sources. Hence the choice of parameters for input variations is based on expert opinion, relevant reports, and interaction with user groups [10,20]. The data used here are considered typical and indicative of the battlefield situations, which could vary widely in different conflicts.

Table 1 gives the number of aircraft and helicopters considered for different types of missions in two cases, namely, case (i) and case (ii). The number of aircraft for ground attack mission, battle area interdiction mission, and for few close air support missions is considered together. For close air support missions, the number provided is the number of helicopters.

In Table 2, we provide the ranges of the uniform distribution considered for different missions and the number of sorties. The number of counter-air missions from 5th day to the end of 2nd week is considered to be two. The battle area interdiction missions are considered to be two from 5th day to the end of simulation. The tons of weapons to be used in any mission are uniform in the interval (1,8). The weight of weapons considered on the first day is 175 tons.

Mission Type Cases	Counter-air	Ground Attack, Battle Area Interdiction, and Close Air Support	Close Air Support
Case (i)	75	150	120
Case (ii)	50	100	80

Table 1. Number of aircraft and helicopters for different missions

Days	Counter-air				Ground Attack				Battle Area Interdiction				Close Air Support			
	Mission		Sorties		Mission		Sorties		Mission		Sorties		Mission		Sorties	
	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
1–2	3	10	2	16	3	5	3	15	-	-	-	-	-	-	-	-
2–4	2	6	2	16	2	6	3	15	-	-	-	-	-	-	-	-
5–14	-	2	2	16	0	3	3	15	-	2	4	12	10	15	4	20
14–28	-	-	-	-	-	-	-	-	-	2	4	12	10	15	4	20

Table 2. The uniform distribution ranges for the number of missions and sorties for different days of battle simulation

In Table 3, we give the logistic requirement probabilities for spares, crew, and equipment, and the 50th and the 80th percentiles of the lognormal distribution for logistic delay times due to spares, crew and equipment. Table 3 also gives the calculated μ_{ls} and σ_{ls} parameters of the corresponding normal distribution for spares, crew, and equipment. Table 3 also provides the logistic delay time distribution parameters for the weapons.

In Table 4, we provide for each subsystem, the set of TBO used in the simulation, the battle damage probabilities (p), the Weibull parameters (β and η), and the repair time distribution parameters (MTTR). The battle damage probabilities and the repair time distribution parameters are the ones reported in the IDA paper for the South Asia War. The other parameters are based on the data available in the literature and expert opinions available to the authors. We note we considered the data provided in Table 4 in an earlier paper [2]. In Table 4 we provide the Weibull and the repair time distribution parameters and the battle damage probabilities for the different subsystems of the helicopters considered. In the present simulation, as a typical example, the battle damage rate is taken as the number of aircraft/helicopter damaged per one thousand sorties as 20 on the first 3 days and 15 from the 4th day to the end of the 2nd week and 8 per thousand sorties from the 2nd week, to the end of the simulation, 28 days.

S1. No.	Logistic Factors	q	80th and 50th percentiles				Calculated μ_{ls} and σ_{ls}			
			M_{80} (Hours)		M_{50} (Hours)		Optimistic		Pessimistic	
			Opt	Pes	Opt	Pes	μ_{ls}	σ_{ls}	μ_{ls}	σ_{ls}
1	Spares	0.5	12	18	6	9	1.7918	0.8252	2.1972	0.8252
2	Crew	0.3	8	12	4	6	1.3863	0.8252	1.7918	0.8252
3	Equipment	0.2	14	21	8	12	2.0794	0.6662	3.0445	0.6662
Weapons										
1	Weapons	-	8		4		2.0794	0.8252	-	

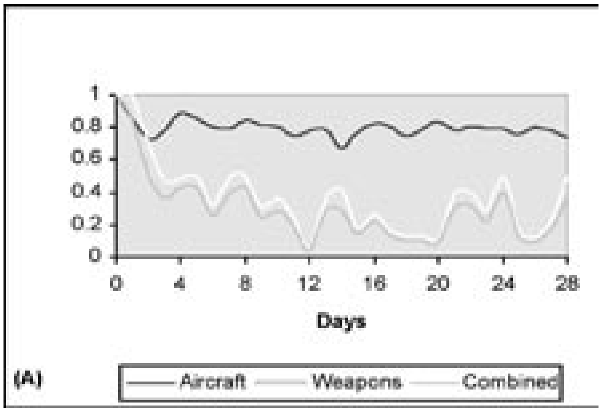
Table 3. Logistic requirement probabilities and the logistic delay time distribution parameters

Fighter Aircraft						
S1. No.	Subsystem	TBO (Hours)	P	Weibull Parameters		MTTR (Hours)
				β	η (Hours)	
1	Structures	5,000	0.4886	3.4	10,000	8.4
2	Flight Control	500	0.0809	2.0	400	30.6
3	Propulsion	300	0.1019	2.1	300	17.8
4	Fuel System	300	0.1214	1.7	300	5.0
5	Power System	300	0.0935	1.1	1,000	35.0
6	Avionics	300	0.0607	2.0	500	5.0
7	Crew Station	1,000	0.0302	2.0	600	20.0
8	Armament Fitments	2,000	0.0228	2.5	1,000	5.0
Helicopter						
1	Helicopter Main Rotor	200	0.3	3.0	1,000	20
2	Helicopter Engine	150	0.4	4.0	500	24
3	Tail Rotor	300	0.3	3.0	3,000	18

Table 4. TBO, battle damage probabilities, failure, and repair time distribution parameters

5.2 Results

The simulation results are shown as graphs of availability vs. battle day for the data used in the simulation. In Figure 2, the availability of the fighter aircraft (dark grey curve), weapons (white curve), and aircraft and weapons combined (light grey curve) are shown for two different configurations of aircraft and logistic delay parameters. To comprehend the effect of logistic delay on the availability, the availability figures at the end of 1, 7, 14, 21 and on the 28th day were analyzed (Tables 5, 6, 7).



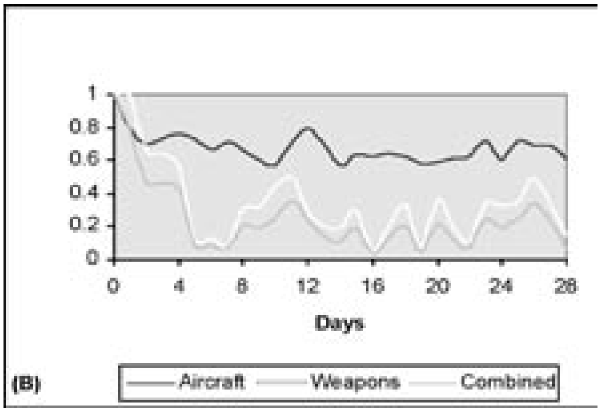
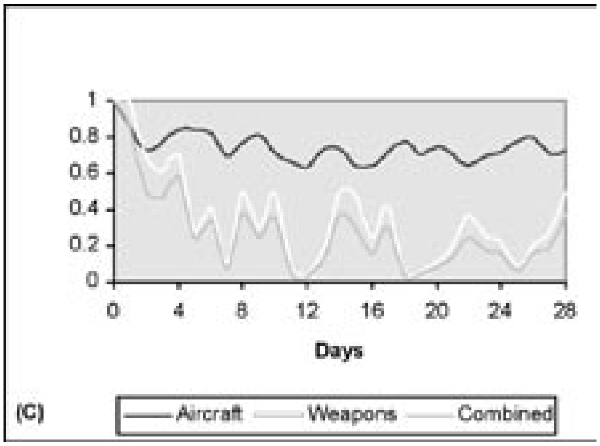
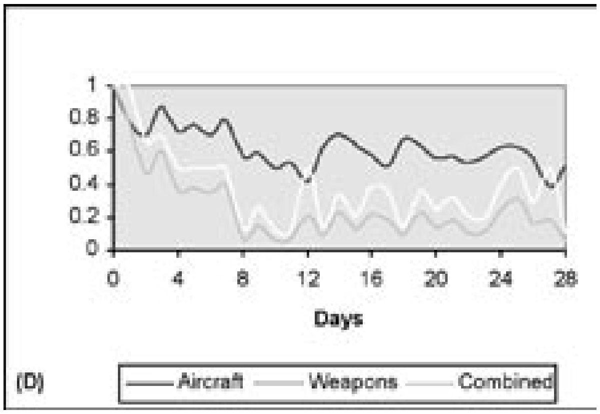
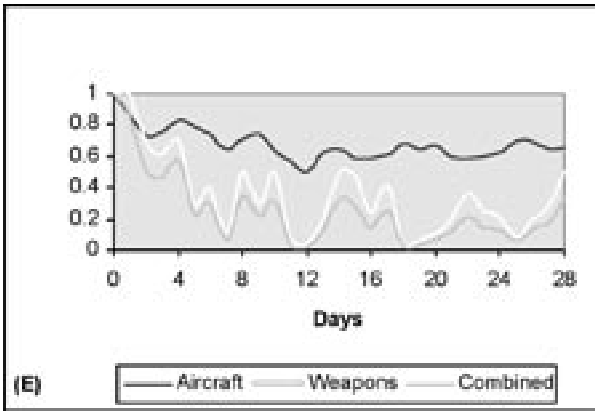
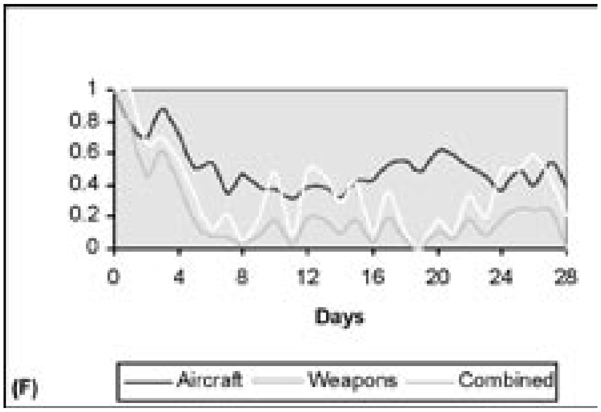


Figure 2. Graphs of availability vs. days for different combinations of aircraft (A/C) and logistic delay (LD) parameters. (A) A/C: Case (i), No LD (B) A/C: Case (ii), No LD (C) A/C: Case (i), LD: Optimum (D) A/C: Case (ii), LD: Optimum (E) A/C: Case (i), LD: Pessimistic (F) A/C: Case (ii), LD: Pessimisitc









Aircraft	Days Availability	1	7	14	21	28
Case (i)	Aircraft	0.861	0.794	0.670	0.777	0.739
	Weapons	1.000	0.500	0.419	0.400	0.500
	Combined	0.861	0.397	0.281	0.311	0.370
Case (ii)	Aircraft	0.796	0.713	0.565	0.609	0.604
	Weapons	1.000	0.091	0.195	0.195	0.156
	Combined	0.796	0.065	0.110	0.119	0.064

Table 5. Availability for different days without logistic delays for aircraft repair

Aircraft	Days Availability	1	7	14	21	28
Case (i)	Aircraft	0.861	0.693	0.733	0.710	0.730
	Weapons	1.000	0.100	0.500	0.198	0.500
	Combined	0.861	0.069	0.367	0.141	0.365
Case (ii)	Aircraft	0.796	0.791	0.704	0.570	0.513
	Weapons	1.000	0.500	0.333	0.325	0.104
	Combined	0.796	0.369	0.234	0.185	0.053

Table 6. Availability for different days with logistic delay parameters being optimistic

Aircraft	Days Availability	1	7	14	21	28
Case (i)	Aircraft	0.861	0.646	0.646	0.603	0.661
	Weapons	1.000	0.100	0.500	0.198	0.500
	Combined	0.861	0.064	0.323	0.119	0.330

Table 7. Availability for different days without logistic delay parameters being pessimistic

The graphs clearly show the fluctuations in the availability of the aircraft, weapons, and the weapon system. Due to considerable variations in weapons availability, the observed fluctuation in the weapon systems availability is significant.

From the graphs (A) and (B) and Table 5, we see that, considering multiple failures and without logistic delay in the repair process, the availability of aircraft at the end of second week (i.e., on the 14th day) is 67% which increases to nearly 78% at the end of 3rd week (i.e., on the 21st day) for the initial deployment of Case (i) aircraft. For the initial deployment of Case (ii) aircraft, the availability at the end of 2nd week is 56%, which increases to nearly 61% at the end of 3rd week. When this availability is combined with the weapons availability, the availability of the weapon system at the end of 2nd week comes down to 28%, which increases only marginally (i.e., to 31%) at the end of 3rd week for the initial deployment of Case (i) aircraft. For the initial deployment of Case (ii) aircraft, the availability at the end of 2nd week is 11%, which increases to only 12% at the end of third week. This clearly shows the effect of weapons availability on the weapon systems availability.

Further, when the logistic delay is considered to be pessimistic in the repair process (Graphs (E) and (F) and Table 7), the availability of aircraft becomes 65% for Case (i) aircraft and 33% for Case (ii) aircraft at the end of 2nd week. This decreases to 60% for Case (i) aircraft and increases to 59% for Case (ii) aircraft at the end of 3rd week. When combined with the weapons availability, the availability of the weapon system becomes 32% for Case (i) aircraft and 10% for Case (ii) aircraft. While at the end of 3rd week, the availability further decreases to 12% and 6% for the two cases of aircraft respectively. This variation in availability also could be due to the air-to-air operations which is considered only until the end of 2nd week and the land-air operations which is extended until the end of simulation (4th week).

To summarize the results further we note the following:

(i) When logistic delays are not considered for the logistic factors, we do not observe much fluctuation in the availability of aircraft. However, the weapons availability has fluctuations, which introduces fluctuations in the weapons systems availability. The minimum values (less than or equal to 5%) for the combined availability found over a period of 28 days are:

Case (i): 4% on 13th day.
Case(ii): 4% on 17th day, 5% on 19th day.

(ii) When logistic delays for the logistic factors in the repair process are considered to be optimistic, we observe moderate fluctuation in the availability of aircraft. The fluctuation in the weapons availability has the effect on the combined availability. The minimum values for the combined availability observed here are:

Case (i): 3% on 12th and 18th day, 4% on 19th day, 5% on 11thth day.
Case(ii): 5% on 28th day

(iii) When logistic delays for the logistic factors in the repair process are considered to be pessimistic, we observe significant fluctuation in the availability of aircraft. Along with the fluctuation in the weapons availability the combined availability fluctuates significantly. The minimum values for the combined availability observed in this case are:

Case (i): 2% on 12th day, 3% on 18th day, 4% on 11th and 19th days.
Case(ii): 0.3% on 19th day, 0.4% on 28th day, 2% on 8thand 11th days, 4% on 16th day, 5% on 18th day.

6. Discussions and Conclusions

The simulation model developed in the present paper enables estimation of availability of weapon systems under battlefield conditions with air-attack missions. The input conditions can be varied to simulate specific battle conditions and combat operations, as well as the number of subsystems considered. In the present simulation model, we have considered air-to-air operations and land-air operations. Under air-to-air operations, counter-air and ground attack missions (air-to-ground missions) are considered. The battle area interdiction and close air support missions are considered under land-air operations. An attempt has been made to distinguish the type of aircraft considered for different missions in practice by considering both fixed wing and rotary wing aircraft.

From the simulation results, it can be emphasized that focus should be made on logistic delays with reference to weapons availability, i.e., the logistic delay time for weapons replenishment, which is assumed to be lognormal. The weapons availability undergoes fluctuations, reaching minimum values of about 3% on certain days. This is an important conclusion. Therefore, the combined availability also reaches very low values on certain days.

Considering two sets of parameter values for the logistic factors noted as optimistic and pessimistic, significant difference is observed in the minimum values of availability of aircraft on specific days. The availability of aircraft alone due to logistic delays can be reduced to less than 40% in some cases. The combined availability is consequently affected.

Further, the simulation results clearly indicate that during high intensity conflicts considering air-attack missions, the availability of weapon systems becomes low within the first few days of the battle. This may lead to either abandoning or postponement of certain combat operations. In such situations possible reinforcement of weapon systems may be required for continuance of battles.

The simulation model developed here can be used to consider the effect of operational parameters such as varying the limits of the number of missions and the number of sorties, reducing the logistic delay and improving the maintainability parameters under different distributions for improving availability.

For recent conflicts, specific data on battlefield conditions are sparsely available. Therefore the results obtained can only be validated with limited data and expert opinions. This limitation is always felt in this field of combat related simulations.

The model developed here can also be suitably modified and applied to other weapon systems such as warships, battle tanks and artillery guns.

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