INTEGRATION OF SURVIVABILITY ASSESSMENT INTO COMBAT AIRCRAFT DESIGN FOR OPERATIONAL EFFECTIVENESS

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Abstract

In this study, a methodology for combat aircraft design will be introduced by using the Unmanned Air Vehicle, U-99, as the case study (Fig. 1). The methodology aims at integration of the survivability assessment into the early stage of combat aircraft design for operational effectiveness. By using the shotline and square counting methods, the vulnerability probability values of the U-99 can be evaluated. The external shape has been separated into several simple geometrical shapes for detection probability prediction. The reliability and maintainability values can be predicted using the Pareto distribution and historical data analysis. Reliability block diagrams have been chosen for developing the flight phase probability in each sortie throughout the mission simulation. This enables the number of available aircraft to be found. Several parameters may be varied to see what effect they have. An optimiser then indicates how effective conceptual design changes may be on producing optimum effectiveness.

1 Introduction

New generations of combat aircraft need be more operationally and cost-effective. This paper will describe the development of a suitable methodology for use in aircraft conceptual design, where most benefits can be produced.

Several aspects and methodologies were considered, such as Reliability & Maintainability (R&M); Supportability; Survivability and Life Cycle Cost (LCC).[1] [2] [3] and [4] have developed methodologies, designed to integrate models of aircraft component effectiveness and life cycle costs into either the conceptual or preliminary design processes. One such methodology integrates operation simulation and cost estimation into the early design process at the same time as the other design disciplines, such as Survivability, Reliability and Maintainability [5]. This paper describes the extension of this methodology to include integration of all necessary design disciplines, but will concentrate on Susceptibility, Vulnerability, and Operation Simulation. The other disciplines will be held as default constant parameters.

"Bombing Mission" has been chosen as a baseline for calculation of operational effectiveness. There are many measures used to evaluate, how effective an aircraft is, such as sortie rate, availability rate, targets destroyed. The "Bang per Buck" philosophy is an alternative objective, which evaluates the optimal ratio between the total operational cost and number of destroyed targets. For this paper, the cost evaluation module is still not available; thus, the main objective will be maximum number of successful sorties.

Due to restricted information available to validate the methodology, the Cranfield Unmanned Air Vehicle, U-99, has been chosen [6] as a case study (see Fig. 1).

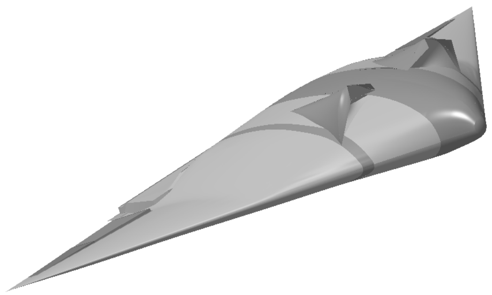

Fig. 1 Drawing of the Cranfield U-99

2 Methodology

This design methodology is based on two fundamental design aspects; the conventional design process and the system of systems. The conventional design methodology can be divided into three major phases, ie. Conceptual, Preliminary and Detail Design [7]. Design parameters for this methodology will be in the form of the basic shape and size of airframe and of components. Aerodynamic variables will be fixed in the conceptual design process, based on traditional performance and mission requirements. Any change of design parameter, performance and/or mission requirements in preliminary and/or detail design stage can result in cost and time problems.

[3] defined an alternative design methodology, the operational design aspect, which integrates survivability assessment into the preliminary design process. By this method an aircraft is treated as a sub-system of the overall system, which represents an operation or campaign. Aircraft performance is measured and used to access the "goodness" of the system. The aircraft operational effectiveness in the theatre level can be measured by transforming performance measures into effectiveness measures, such as probability of kill, detection, defect arising rate and mean time between repair.

Fig. 2 shows a proposal for integration of the conventional design process and operational design aspects. This methodology intends to integrate all design aspects into the early design stage, conceptual and preliminary, with operational and cost effectiveness considerations.

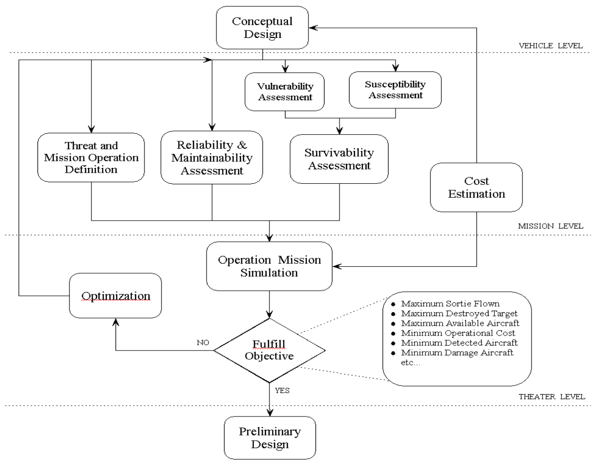

Fig. 2 Flowchart for operational and cost effectiveness design methodology

3 Operation simulation

The operation simulation Module is the main trunk of this methodology, as it links all the design aspects and shares information between design aspects to evaluate aircraft effectiveness for a specific mission. For this study, the "Bombing mission" has been chosen.

[8] calculated the number of available, damaged, or destroyed aircraft directly from mission probability at the end of sortie and operational day. The result could be a floating number with decimal notation. Simple optimisers require results in integer number form, so [9] used operation time, t, to check the aircraft status at the end of sortie, to see whether the aircraft required maintenance or could return to the fleet.

In this study, a sortie is divided into five phases, ie Preflight, Outbound, Attack, Inbound and Postflight Phases. In each phase aircraft have different flight characteristics and performance, and also occupy different distances from threats, thus the probability values of aircraft effectiveness have to be evaluated separately. The reliability block diagram (RBD) technique has been chosen to be used for the calculation of the probability values of flight phase success, maintenance, damage, kill, and so on. Each aircraft will have separate phase success probability, due to random encounters. The number of available aircraft in each phase, sortie and operation day are thus in the form of integer numbers.

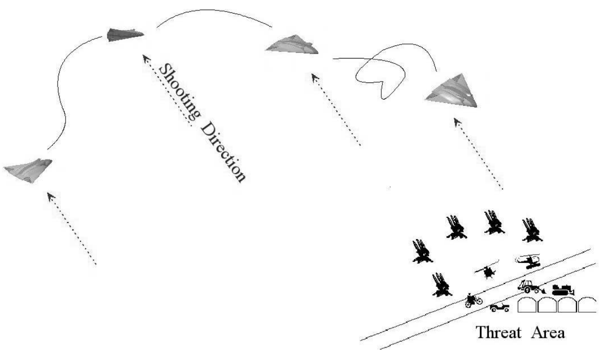

Fig. 3 Sample of different flight characteristic in a mission

In the operation simulation module, in each flight phase the aircraft will have different flight characteristics, such as the percentage the front view faces to the threat (See Fig. 3). The result is that the survivability probability in each flight phase will be different. An alternative way to evaluate these values is to use weighting factors for each view in each flight phase.

Table 1 Percentage of Weighting factors for option 2 for each view in flight phases

Flight phase	Top	Right	Left	Front	Rear	Bottom
Preflight	25	0	0	75	0	0
Outbound	5	15	15	60	0	5
Attack	15	15	15	40	0	15
Inbound	5	15	15	0	60	5
Postflight	25	0	0	0	75	0

4 Survivability

Aircraft combat survivability is the capability of an aircraft to avoid and/or withstand a man-made hostile environment and the survivability assessment process can be divided into several parts to determine the effectiveness of the aircraft for the given campaign[10].

Aircraft survivability can be measured by the parameter P_S, the probability of survival, which in turn is related to the probability of kill, P_k, by the following equation:

$$P_S = 1 - P_k \tag{1}$$

Aircraft kill probability is the product of two survivability concepts: susceptibility, P_H, and vulnerability, $P_{K/H}$.

$$P_k = P_H \cdot P_{K/H} \tag{2}$$

The result is that the survivability will be enhanced when susceptibility and vulnerability are reduced as following relationship:

$$P_S = 1 - P_H \cdot P_{K/H} \tag{3}$$

In many combat situations an aircraft might be shot at several times by one weapon and/or more. It is assumed that each threat can encounter only one aircraft and be independent. The aircraft mission survivability depends on number of encounters and type of weapons. An aircraft can survive from the mission only when it survives each encounter during the mission, and the probability the aircraft survives in ith encounter refers to its $(i-1)$th encounter survivability probability (see figure 4).

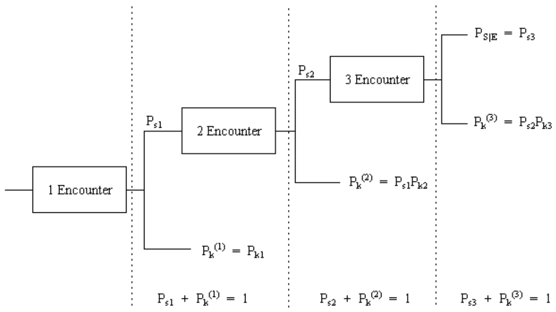

Fig. 4 Block diagram for independent encounters survivability probability

The aircraft survives the encounters when it survives all shots; therefore the encounter survivability probability can be determined as follows:

$$\begin{aligned} P_{S|E} &= P_{S1}P_{S2}P_{S3} = (1-P_{K1})(1-P_{K2})(1-P_{K3}) \\ &= 1 - P_{K|E} \end{aligned} \tag{4}$$

If an aircraft encounters several weapon types; each type has expected number E_i. The aircraft mission survivability is calculated as follows:

$$P_{S(\text{mission})} = P_{S(\text{weapon type 1})} P_{S(\text{weapon type 2})} \cdots P_{S(\text{weapon type I})} \quad (5)$$

where

$$P_{S(i\text{th weapon type})} = (1 - P_{Ki})^{E_i} = \exp(-E_i P_{Ki}) \quad (6)$$

4.1 Susceptibility assessment

Susceptibility is the probability that the aircraft will be detected and be hit. This value is a function of those things that would make the aircraft more difficult to be seen and tracked, such as stealth, maneuverability, tactics, and avionics. The probability of hit, susceptibility, can be divided into five phases with conditional probabilities, ie. probability of the threat being active when the aircraft arrives (P_A); the probability of the aircraft being detected given the threat is active ($P_{D/A}$); the probability of the threat weapon being launched, given the threat is active and detects the aircraft ($P_{L/D}$); the probability that the threat weapon intercepts the aircraft given the threat propagator was launched ($P_{I/L}$); and the probability that the threat propagator hits the aircraft or the proximity warhead fuzes, given the propagator intercepts the aircraft. The conditional probability of hit is ($P_{H/I}$ or $P_{F/I}$).

$$P_H = P_A P_{D/A} P_{L/D} P_{I/L} (P_{H/I} \text{ or } P_{F/I}) \quad (7)$$

4.1.1 Radar cross section

Radar Cross Section (RCS) is a measurement value used to estimate the size of the aircraft signature, σ, by using the transmitting and receiving radar signal collocation. One unit of measurement of σ is the square meter, and another is the decibel (dB), where the reference level is usually 1 $m^2(dB_{sm})$. The RCS depends strongly upon the direction from which the signal arrives and the direction of the receiving antenna. The total cross section of a complex aircraft can be computed by an assembly of simpler shapes and by a number of techniques of different levels of complexity [11]. A simple approximation, called the *random phase method*, simply averages the contributions of the σ_k's over all possible phase angles. This leads to the formula:

$$\sigma_{total} = \sum_{k=1}^{N} \sigma_k \quad (8)$$

[12] described the equation and how to calculate the probability of detection (P_d), which is a function of antenna characteristics such as Signal-to-Noise Ratio (S/N), Loss factor (L), probability of false alarm (P_n) and so on. Starting with the fundamentals of radar systems, the S/N is a function of target cross section and radar system characteristics as:

$$\frac{S}{N} = \frac{PG^2\lambda^2\sigma}{(4\pi)^3 FkTB_nL} \quad (9)$$

where P is the radar power; G is the gain of the antenna; λ is radar wave length; σ is target cross section; FT is the effective noise temperature; B_n is equivalent received noise bandwidth; L is the loss factor and k is the Boltzmann's constant.

Thus the probability of detection can be determined as follows:

$$P_d = 1 - e^{-S/N} \int_{P_n}^{1} I_0 \left\{ \sqrt{-4\frac{S}{N} ln(u)} \right\} du \quad (10)$$

where

P_d = Probability of Detection
S/N = Signal to Noise Ratio
P_n = Probability of False Alarm
I_0 = Hyperbolic Bessel Function of zero order

Due to complex integration and the effect of significant fluctuations in the magnitude of σ seen by the radar (the scintillation phenomenon), an alternative to evaluate the detection probability of the target cross section is to use fig.5.

4.1.2 Conditional probability of hit

This probability value depends on the threat weapon type which intercepts the aircraft, and

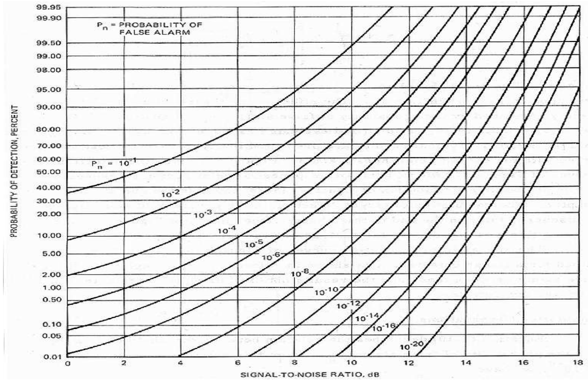

Fig. 5 Probability of Detection[12]

whether it has a contact warhead ($P_{H/I}$) or a proximity warhead ($P_{F/I}$).

The probability that the aircraft is hit, given the intercept, $P_{H/I}$, depends upon the miss distance and upon the physical size of the aircraft presented area to the propagator. We assume that an aircraft has been shot with N propagators at N locations of x,y pairs. The distance from the aircraft aim point to any x,y pair is the miss distance for that shot, and the distances x and y are the coordinate errors. The frequency of the miss distance $\rho(x,y)$ can be expressed as:

$$\rho(x,y) = \frac{1}{2\pi\sigma_x\sigma_y} \exp\left(-\frac{(x-\mu_x)^2}{2\sigma_x^2} - \frac{(y-\mu_y)^2}{2\sigma_y^2}\right) \quad (11)$$

where the mean μ_x and μ_y and the standard deviations σ_x and σ_y relate to the sample means and variances. For the general aircraft whose extent in the intercept plane is defined by the two-dimensional function $L(x,y)$, the probability of a propagator hit on the aircraft is given by:

$$\begin{aligned} P_{H/I} &= \iint_L \rho(x,y)dxdy \\ &= \iint_L \frac{1}{2\pi\sigma_x\sigma_y} \exp\left(-\frac{(x-\mu_x)^2}{2\sigma_x^2} - \frac{(y-\mu_y)^2}{2\sigma_y^2}\right) dxdy \quad (12) \end{aligned}$$

To compute the probability of the above equation, two alternative aircraft shape representation have been used, the "shoe box" and "Carlton" or the diffused Gaussian [10]. If circular symmetry about the aim point is assumed for the miss distance distribution, and if the aircraft presented area is taken as a circle of radius r_0 and $\sigma_x = \sigma_y = \sigma_r$ the $P_{H/I}$ can be estimated from one of following equations:

Shoe Box

$$P_{H/I} = 1 - \exp\left(\frac{-A_p}{2\pi\sigma_r^2}\right) \quad (13)$$

Carlton

$$P_{H/I} = \frac{A_p}{2\pi\sigma_r^2 + A_p} \quad (14)$$

where $\pi r_0^2 = A_p$.

On the other hand, the propagator with a proximity warhead does not have to hit the aircraft to kill it (see Fig. 6). Instead, the aircraft is killed when the proximity warhead fuzes in a location that causes one or more warhead fragments or penetrators to hit the aircraft and these hits are sufficient to kill the aircraft. The number of fragments that hit the aircraft depends on the number and the location of the fragment impacts and on the terminal effects parameters, such as the fragment mass and impact velocity. Once the number of fragments along the aircraft length can be evaluated, all fragments will hit the aircraft. In this case, the probability of fuze, $P_{F/I}$, become value of 1.

$$n = \rho A_p \quad (15)$$

$$\rho = \frac{N}{2\pi s^2(\cos\phi_1 - \cos\phi_2)} \quad (16)$$

where n is the number of hits on the aircraft, ρ is the average number of fragments per unit area of fragment spray, knows as the fragment spray density, A_p is the aircraft presented area at the aspect, N is the total number of fragments in the warhead, s is distance from detonation point to the fragment spray, and ϕ_1 and ϕ_2 are the leading and trailing fragment spray angles.

4.2 Vulnerability assessment

Vulnerability is the probability that the aircraft will be killed if hit; and is a function of detailed aircraft configurations, including specific armament, system locations and redundancies. Aircraft consist of many components, and each individual component has a level of vulnerability, thus each component's vulnerability contributes

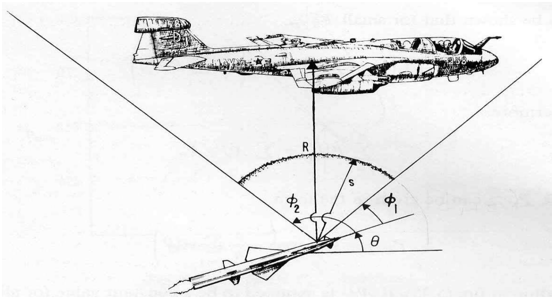

Fig. 6 Assumed encounter with a horizontally moving Aircraft [13]

in some measure to the overall vulnerability of the aircraft [10]. There are four major categories for calculating the probability of the vulnerability value. These are the shotline assessment technique, vulnerable area assessment, internal burst assessment, and endgame analysis. For this study, the third and the fourth categories will not be considered because the threat in this study is limited to the penetrator and single fragment damage mechanisms.

4.2.1 Shotline

[9] used the Shotline technique with the solid modelling CAD technique to evaluate aircraft kill probability. A planar grid was superimposed over the aircraft and parallel shotlines from the threat direction were passed towards the grid nodes. A list of the penetrated components was generated. These components were then used to quantify the aircraft kill probability, based on the threat intensity and direction.

4.2.2 Vulnerable Area

Vulnerable area is a theoretical threat-presented area that, if hit by a damage mechanism, would result in an aircraft kill. The vulnerable area of the ith component, A_{v_i} depends on the presented area of the component in the plane normal to the approach direction of the threat (A_{p_i}) and the probability of kill of the component, given a hit on the component (P_{k/h_i}) as following:

$$A_{v_i} = A_{p_i} \cdot P_{k/h_i} \tag{17}$$

The kill probability of the ith component given a random hit on the aircraft P_{k/H_i} is the product of the probability the component is hit, given the hit on the aircraft P_{h/H_i} and the probability that the component is killed, given a hit on the component P_{k/h_i}. Thus:

$$P_{k/H_i} = \frac{A_{v_i}}{A_p} \tag{18}$$

This form of vulnerability assessment is the simplest to perform and was chosen for this study.

4.2.3 Kill probability of aircraft using the vulnerable area method

The calculation of the probability value of aircraft kill ($P_{k/H}$), is the summation of the kill probability values of each critical component. The $P_{k/H}$ for each view aspect is slightly different because of the projected area of critical components, location of overlapped critical component and probability of kill of critical components.

By using a less critical component as a shield and duplicating the critical components are alternatives of vulnerability reduction enhancement. One of the difficulties in vulnerability assessment is estimation of P_{k/h_i}, it needs experiment or great experience. Therefore, the P_{k/h_i} values used in this study are set up as default (see Table 2).

Table 2 Default $P_{k/h}$ values

Critical component	$P_{k/h}$
Pilot	1.0
Fuel	0.3
Engine 1	0.6
Engine 2	0.7
Avionic	0.8

By using a Markov chain, or the state transition matrix method, the kill probability of multiple hits by fragment or nonexplosive penetrators can be calculated. This method can handle the problem of redundancy by assuming no increase in the ith component probability of kill, P_{k/h_i}. The sum of the elements of state vector $S^{(j)}$ is unity and the kill probability of aircraft given j hits is defined by the states that specify either a kill of any of the nonredundant components ($Knrc$) or a kill of the members of the sets of redundant components (Krc).

$$\{S\}^{(j)} = \begin{Bmatrix} Knrc \\ ke1 \\ ke2 \\ \vdots \\ Krc \\ NK \end{Bmatrix}^{(j)} = [T]\,\{S\}^{(j-1)} \quad (19)$$

and

$$P_{K/H}^{(j)} = Knrc^{(j)} + Krc^{(j)} \quad (20)$$

The proximity-fuzed high explosive warhead produces primary damage from blast and high velocity fragments or penetrators generated by the detonation. The blast effect in this study is not considered due to external detonation and complexity of estimation. On the other hand, the fragment effect depends on detonation distance, number of fragments, velocity and direction of missile and aircraft. The Markov chain, binomial approximation and Poisson approach may be used to determine the probability of an aircraft being killed after being hit by N fragments. The binomial approximation, based the distribution of fragments in a fragment spray zone, assumes that the number of fragments that hit the aircraft is a random number. The N hits by the Poisson approach are assumed to be uniformly distributed over a spray zone.

5 Reliability & Maintainability

Reliability can be quantified as the probability of successfully completing the mission without failure, and maintainability concerns the ability to be maintained. The probabilities of reliability and maintainability values are evaluated and integrated into the operation simulation module. Due to lack of system and component details during the conceptual and preliminary design stage, historical data were statistically analysed and used to develop prediction techniques.

[14] developed equations to estimate defect rate (DR) and defect man-hour rate (DMHR) of thirteen main systems for both combat aircraft and jet airliners. The method chose two design parameters for each system based on correlation and technical relationships. On the other hand, [9] used the Pareto distribution to predict the total aircraft failure rate (FR) and established equations for the highest and lowest failure-rate figures, and the number of system per aircraft.

The difficulties in estimating reliability are design age and advanced technology factors of aircraft systems; therefore those effects will not be considered in this study. From data in [9] and [14] the 40:70 Pareto distribution has been found and used to predict the total failure rate. This means that 40% of total systems led to 70% of the total aircraft failure rate (See Fig. 7).

The scheduled maintenance effort is based mainly on aircraft mass and thrust [15]; unfortunately this effort will not be of concern in this study due to the simulating war time not peacetime operations .

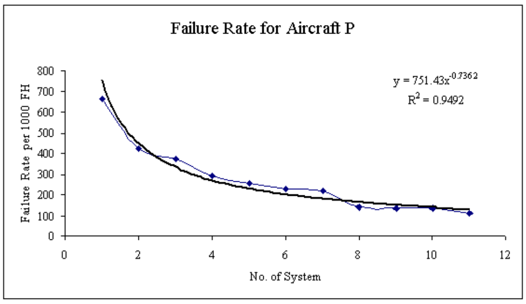

Fig. 7 Pareto distribution for system failure rates

6 Life Cycle Cost

Life Cycle Cost (LCC) can be divided into five major portions, ie. research, development, test and evaluation (RDT&E); production; ground support equipment and initial spares (GSE&IS); operation; and disposal cost. [4] showed that around 70% of the total LCC of the last generation of combat aircraft is spent on the operation and support costs. It also described the methodology used to minimise combat aircraft life cycle cost in peace time through conceptual design. Most cost models in this work were based on aircraft, systems and components mass; thrust; number of aircraft and personnel factors.

The operation and support costs include operation (mission) personnel; support personnel; service allowances, personnel support, and training; unit level consumption; contract costs for airframe, avionics and propulsion; sustaining support funds; and basing overheads and upkeep. For the current study, some modifications will be done to establish the appropriate operation and support cost models.

Maintainability effort is one of the largest elements of operation and support costs, and it is also particularly difficult to predict at the conceptual design stage due to lack of detailed systems and component information. [15] presented a methodology to predict the cost of maintenance from the total arising maintenance effort and the total scheduled inspection and maintenance effort, and this approach will be used.

7 Methodology optimisation approach - Genetic Algorithms

Due to the integer number of objective values, the gradient-based optimisation method is not appropriate to this study. An alternative is the genetic algorithm method (GA). This search methodology is based on the mechanics of natural selection and natural genetics. They combine survival of the fittest among string structures with a structured yet randomized information exchange, to form a search algorithm with some of the innovation flair of human search methods. In every generation, a new set of artificial creatures (string) is created using bits and pieces of the fittest of the old; an occasional new part is tried for good measure [16].

[17] provides a program library in the C++ langauge, and offers several methods of stop criterion, such as number of generations, goodness-of-best solution, convergence-of-population, and also can be self defined problem-specific criterion. This library was used for optimising the operation simulation module.

8 Results with the U-99 Test Model

Once the RCS of the U-99 had been calculated as 0.00610207 m^2, the probability of detection and probability of hit for both for penetrator and external explosion could be evaluated and then fed into the operation simulation module. The probability of detection and probability of hit were then held as constants throughout the simulation.

Table 3 shows the results of the U-99 kill probability given a hit by a single penetrator with and without the shielding effect of critical component overlapped area. In the shielded effect case, the overlapped critical component will survive after the first hit and decrease its P_{k/h_i} by 10%. The result is a reduction of aircraft kill probability and vulnerable area.

Table 3 Kill probability of U-99 by single penetrator with weighting factor option 2 in attack phase

View	No shielding effect	Shielding effect
Top	0.05876994	0.05902689
Right	0.21187566	0.12471783
Left	0.21187566	0.12471783
Front	0.25742697	0.20224718
Rear	0.25742697	0.17752809
Bottom	0.05876994	0.05902689
Total	0.18416446	0.13602222

In the operation simulation, each aircraft encounters two different main threats; nonexplosive and external explosive threats. The number of encounters and the detonation distances in each phase, and for each aircraft are random. Table 4 shows an example for the kill probability of U-99 by encounters from the two main threats.

Fig. 8 shows the effect of weighting factors on the total number of sorties flown, successful sorties and complete sorties. The weighting factors vary the percentage of exposure of the aircraft to each of six main views and will vary according to flight phases (see Table 1 for an example of option 2). The Option 5 produces more successful sorties because the aircraft is flown in attack phase such that there was less exposure of the top and bottom views. These views have high

Table 4 Kill probability of U-99 with shielding effect of overlapped area for different Threats for weighting factor option 2 in attack phase

View	Non Explosive		External Explosive	
	1 Hit	20 Hits	14 m	140 m
Top	0.0584	0.7402	0.9984	0.0629
Right	0.1247	0.9423	0.9089	0.0236
Left	0.1247	0.9423	0.9089	0.0236
Front	0.2022	0.9915	0.9559	0.0307
Rear	0.1775	0.9861	0.9355	0.0270
Bottom	0.0584	0.7402	0.9984	0.0629
Total	0.1358	0.9013	0.9545	0.0382

susceptibility but low vulnerability, thus the former dominates.

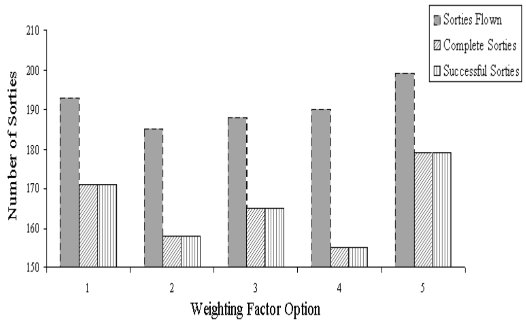

Fig. 8 Result from Operation Simulation module with different weighting factor options

Fig. 9 shows option 2 results from the GALib optimisation program. The maximum of 169 successful sorties is produced with a probability of detection of 0.409442.

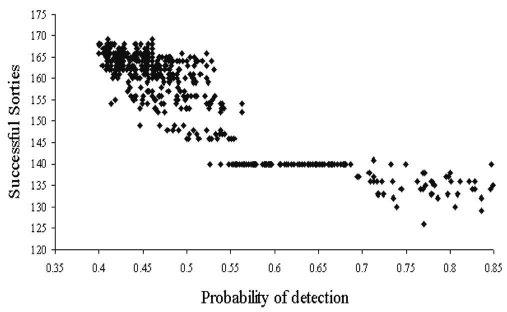

Fig. 9 Result from Optimisation with GALib

9 Conclusion

Alternative ways to increase survivability probability value are to use less critical components as shields, and to increase performance of the aircraft to achieve better weighting factors.

This study has shown that the effects of survivability and weighting factors on the number of successful sorties, complete sorties and sorties flown in the operation simulation. There are other important effects, such as reliability & maintainability, which have not been modeled.

Integer objective values can be evaluated by genetic algorithm optimisation; unfortunately the result are given in the form of a range instead of an exact value.

Future developments of this methodology will search for and integrate the relationships between other design aspects and survivability, such as reliability and life cycle cost. This will increase the effectiveness of the design methodology, to give a fuller representation of realistic aircraft operations.

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