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RANKED OUTCOME APPROACH TO AIR-TO-AIR COMBAT MODELLING

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ABSTRACT

Computer simulation models have been used for many years to assess the overall effectiveness of a military campaign. At the campaign level, engagements (such as air-to-air combat) will invariably be represented at relatively high levels of aggregation. This paper explores the potential for using a ranked outcome approach (rather than a traditional probabilistic approach) to provide an alternative representation of engagements within an air combat simulation.

1 INTRODUCTION

Computer simulation models have been used for many years to assess the overall effectiveness of a military campaign. As well as the representation of the main physical entities, these simulations will involve elements of logistics, command and control modeling and will include representations of intelligence, surveillance and targeting functions. Within the air environment any campaign level simulation model will invariably contain a large element dealing with air combat both in terms of the delivery of weapons in an air-to-ground mode and in assessing the outcome of air-to-air engagements.

At the air campaign modelling level, air-to-air engagement modelling will usually involve a relatively high level of aggregation. Aggregated air combat modelling is certainly nothing new; during the very earliest stages of aviation development Fredrick Lanchester (Lanchester 1916) proposed a series of relationships between attrition, force size and the effectiveness of fire.

An example of a Lanchester equation for Direct Fire (also known as Ancient Combat or Square Law) is

$$dA/dt = -K_d D \text{ and } dD/dt = -K_a A$$

where A represents attacker strength, D represents defender strength, and K represents kill potential for either side. So for Direct Fire the attacker's losses are proportional only to the number of defenders involved in the engagement.

Lanchester equations have remained popular in the intervening century, principally because they seem to be intuitively reasonable. MacKay (2011) achieved reasonable success in matching air to air combat losses during the Battle Of Britain (1940) and the Korean War (1950 to 1953) using Lanchester equations. The problem Lanchester's equations give the analyst however, is to ascertain the input values to use for the terms covering 'kill potential ' – in other words how to predict the likely effectiveness of the weapon system.

In Lanchester's era and up until the middle of the last century, when the key kill mechanism was from direct fire machine guns, the main factors in air-to-air combat were the speed and manoeuvrability of the engaging platforms. Production of a 'kill potential' figure for an individual platform was therefore relatively easy. With the advent of air-to-air missile systems in the 1950's the emphasis was more on the capabilities of the sensor and missile packages on the individual platforms. Generation of a 'kill potential' figure therefore became harder, but was still manageable.

By the 1990s with the introduction of beyond-visual-range missile systems, the key factors in the air-to-air engagement had become the situational awareness of the individual platforms and the ability to provide the required information and decision support to the aircraft cockpit.

As a result, the production of a single 'kill potential' value in modern combat modelling is now much more problematic. For example, quality of information and decision support will invariably be scenario specific, and a single 'kill' value will not account for a single platform having multiple roles, i.e. as a fighter, as a bomber or as a surveillance platform. Similarly a single 'kill' figure will not account for synergies between different force elements, and will not account for diminishing returns on quantity (i.e. there will come a point at which one of the sides cannot utilise any additional assets in an effective manner). And finally, and probably most importantly, the overall aircraft attrition value may not actually be the correct measure of effectiveness for that particular operations.

2 GENERATION OF AIR-TO-AIR KILL POTENTIAL VALUES

In modern aggregated air combat models the values for 'kill potential' will tend to be developed using results from high fidelity models, either man-in-the-loop simulations (for example synthetic environments) or from detailed constructive simulations. The actual values will usually be normalised against a particular platform type and hence can be illustrated in the form of a nomograph (Figure 1) showing expected exchange ratios. Figure 1 is an illustrative nomograph where columns represent platform capabilities. The relative exchange ratio is then obtained by reading the value from a logarithmic scale. In this example, the exchange ratio between 'BlueSystem' and 'RedSystem1' would be 1 to 1 due to the parity of the column values. An engagement between 'BlueSystem' and 'RedSystem2' would result in an exchange ratio of around 2.5 to 1 in favour of Blue. Similarly, an engagement between 'BlueSystem' and 'RedSystem3' would result in an exchange ratio of around 2.5 to 1 in favour of Red.

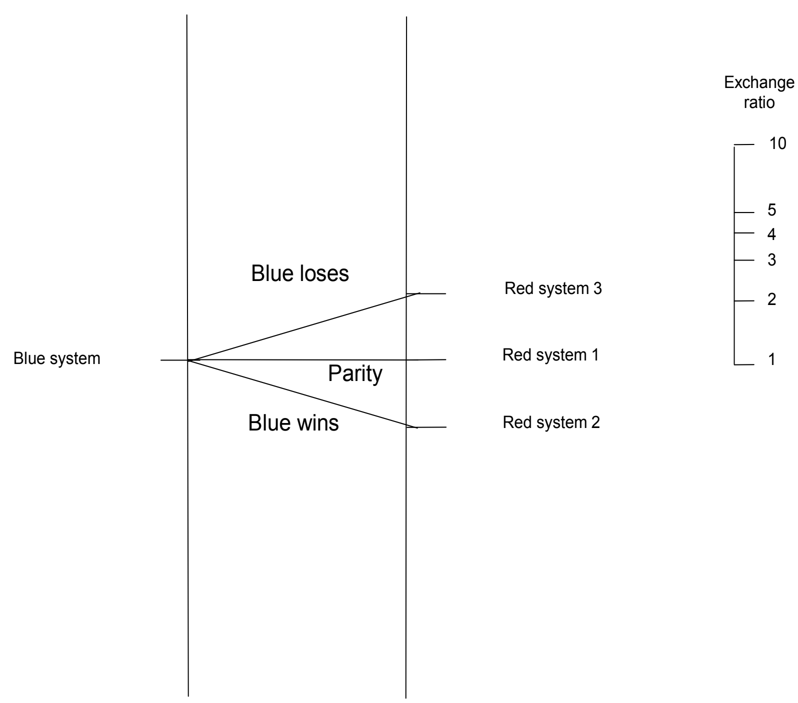

Figure 1: Example Nomograph to Illustrate Exchange Ratios.

There are several assumptions inherent in this type of model;

1. can single engagements be aggregated up to the mission, operational and campaign levels?
2. can values be interpolated between data points?
3. can the model work for non-peer engagements?

To be used within a simulation model, an exchange ratio will need to be converted to some form of kill probability or "kill potential". An exchange ratio of 2 to 1 (in favor of BLUE over RED) could be represented as a kill probability of 0.8 for BLUE and of 0.4 for RED. However the same 2 to 1 exchange ratio could also be represented as a kill probability of 0.4 for BLUE and of 0.2 for RED. In these two cases, the exchange ratios would remain the same but the overall rate of attrition would be different and potentially give rise to a different overall outcome.

3 PROBABILISTIC APPROACH TO ENGAGEMENTS

Aggregated simulation models of air combat typically adopt a probabilistic approach to air-to-air engagements. To illustrate how a probabilistic approach can affect the overall outcome of an engagement, consider a two-sided (A and B) engagement where the probability of success for side A is p_a and for side B is p_b. The outcome of an engagement between a pair of aircraft $a_i b_i$ is determined by sampling two uniform random variables r_a and r_b. If $r_a < p_a$ and $r_b >= p_b$ then a_i wins the engagement, if $r_a >= p_a$ and $r_b < p_b$ then b_i wins the engagement, and if either $r_a < p_a$ and $r_b < p_b$ or $r_a >= p_a$ and $r_b >= p_b$ then the contest is deemed a draw.

As an example, consider the case of a two-sided engagement with each side having 4 aircraft, where there are 15 possible overall outcomes. Table 1 illustrates the possible outcomes and the equations for calculating each of these outcomes.

Table 1: Possible Outcomes for 2-Sided 4-Aircraft Engagement.

Results	Overall Outcome	Probability
4 wins for A	A wins by 4	$(p_a .(1- p_b))$^4
3 wins for A and 1 draw	A wins by 3	4. $(p_a .(1- p_b))$^3 .$((p_a . p_b)+(1-p_a).(1-p_b))$
3 wins for A and 1 win for B	A wins by 2	4. $(p_a .(1- p_b))$^3 .$(1-p_a).p_b$
2 wins for A and 2 draws	A wins by 2	6. $(p_a .(1- p_b))$^2 .$((p_a . p_b)+(1-p_a).(1-p_b))$^2
2 wins for A, 1 draw, 1 win for B	A wins by 1	12.$(p_a .(1- p_b))$^2 .$((p_a . p_b)+(1-p_a).(1-p_b)).((1- p_a). p_b)$
2 wins for A and 2 wins for B	Draw	6. $(p_a .(1- p_b))$^2 .$((1-p_a). p_b)$^2
1 win for A and 3 draws	A wins by 1	4. $(p_a .(1- p_b))$.$((p_a . p_b)+(1-p_a).(1-p_b))$^3
1 win for A, 2 draws, 1 win for B	Draw	12.$(p_a .(1- p_b))$.$((p_a . p_b)+(1-p_a).(1-p_b))$^2.$((1- p_a). p_b)$
1 win for A, 1 draw, 2 wins for B	B wins by 1	12.$(p_a .(1- p_b))$.$((p_a . p_b)+(1-p_a).(1-p_b))$.$((1- p_a). p_b)$^2
1 win for A and 3 wins for B	B wins by 2	4. $(p_a .(1- p_b))$.$((1-p_a).p_b)$^3
4 draws	Draw	$((p_a . p_b)+(1-p_a).(1-p_b))$^4
3 draws and 1 win for B	B wins by 1	4. $((p_a . p_b)+(1-p_a).(1-p_b))$^3 .$(1-p_a).p_b$
2 draws and 2 wins for B	B wins by 2	6. $((p_a . p_b)+(1-p_a).(1-p_b))$^2 .$((1-p_a).p_b)$^2
1 draw and 3 wins for B	B wins by 3	4. $((p_a . p_b)+(1-p_a).(1-p_b))$.$((1-p_a).p_b)$^3
4 wins for B	B wins by 4	$((1-p_a) .p_b)$^4

The results for probability of success $p_a = 0.9$ and for $p_b = 0.8$, 0.7, 0.6 and 0.5 are shown in Figure 2, with the corresponding results for $p_a = 0.8$ and $p_a = 0.7$ shown in Figure 3 and 4 respectively.

Examination of Figures 2, 3 and 4 show how the results from a symmetric engagement quickly become skewed as the relative "kill potential" varies. This is most apparent in the Figure 2 where the spread of outcomes is smallest and the skewness greatest.

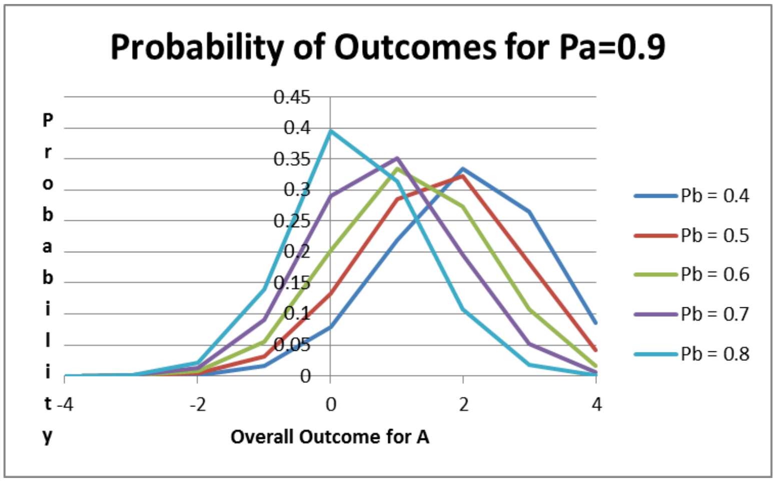

Figure 2: Probability of Outcomes for Different Kill Probabilities for Pa=0.9.

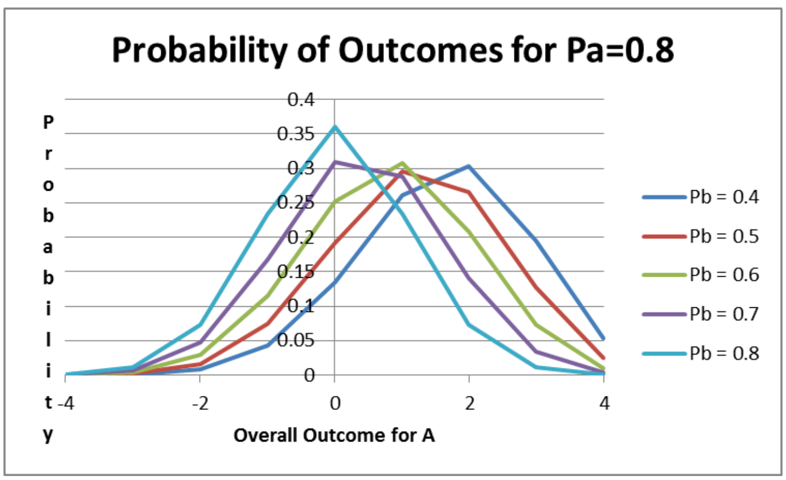

Figure 3: Probability of Outcomes for Different Kill Probabilities for Pa=0.8.

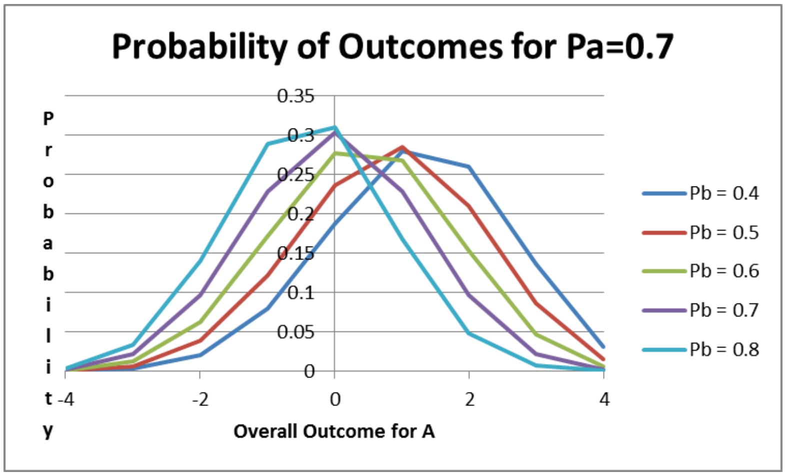

Figure 4: Probability of Outcomes for Different Kill Probabilities for Pa=0.7.

4 HISTORICAL DATA

There are several challenges inherent in using this type of probabilistic approach to air-to-air engagement modeling;

a. can a single probability represent the population space of the combatants?
b. can a single probability represent changes over time as the campaign develops?
c. is the model valid for non-peer engagements?

To answer these concerns, a range of analysis studies (such as MacKay 2011) have investigated historical air-to-air combat during the First World War, Second World War and Korean War. These campaigns tend to involve two sides utilizing comparable technologies and these generally show that, within boundaries, Lanchester type equations give a reasonable indication of air campaign outcomes.

However there has been very little historical analysis of air-to-air combat in the modern era (i.e. in the last 25 years). Although there have been recent air campaigns in areas such as the Balkans, Iraq, Libya and Afghanistan they have involved very little air-to-air combat. While the engagements between Coalition fighters and Iraqi and Serbian Air Force fighters were small in number the Iraqi and Serbian Air Forces suffered high relative attrition in the engagements that did take place, probably significantly higher that a static score on Lanchester type models would have predicted. While the Iraqis and Serbs had had some reasonably capable aircraft platforms, the limited training, limited doctrine, limited support assets and significant maintenance issues (resulting from several years of military sanctions) put these Air Forces at a considerable disadvantage in a combat situation.

Historical analysis within the Land environment has developed empirical evidence for understanding some of the human factors that contribute to combat degradation in real combat situation (Roland 1987, 1991). Historical research within the air environment from the Second World War (Shores 1994) indicate the disproportionate contribution made by a small number of combat pilots (Air Aces) – with evidence suggesting that 5% of fighter pilots accounted for 60% of the total kills

While this research is based on a small sample size, it may suggest that there is a requirement for slightly different sets of rules to take into account the variability in individual performance particularly when applied for ‘non-peer’ type engagements. Cowdale (2004) illustrated that results from professional sport could be used to develop exchange ratios in a similar way to those developed for use in air-to-air combat modeling. However, the results from analysis of English Association Football results do not produce exchange ratios as large as those observed during recent air-to-air combat engagements between non-peer air forces.

5 RANKED OUTCOME APPROACH

To try to address the problem of assessing the likely outcomes from engagements between non-peer competitors while incorporating the variability resulting from human factors, an alternative approach of using ranked outcomes has been explored.

Consider a two-sided (X and Y) engagement with ranked outcomes – one side with aircraft $x_1, x_2, \ldots, x_n$ and the other with aircraft $y_1, y_2, \ldots, y_m$. Engagements between pairs of aircraft are chosen at random with the outcome of the engagement being decided by the relative rank order of each aircraft. So x_i defeats y_j when $i>j$ but x_i loses to y_j when $i<j$. If $i=j$ then the outcome between x_i and y_j is declared a draw. As an example consider the case of a two-sided engagement with ranked outcomes between four aircraft – one side with aircraft x_1, x_2, x_3, x_4 and the other with aircraft y_1, y_2, y_3, y_4. There are 24 possible sets of engagements illustrated in Table 2.

Table 2: 4v4 Engagement Outcomes with No Offsets.

Engagement 1	Engagement 2	Engagement 3	Engagement 4	Overall outcome
x_1 v y_1	x_2 v y_2	x_3 v y_3	x_4 v y_4	Draw
x_1 v y_1	x_2 v y_2	x_3 v y_4	x_4 v y_3	Draw
x_1 v y_1	x_2 v y_3	x_3 v y_2	x_4 v y_4	Draw
x_1 v y_1	x_2 v y_3	x_3 v y_4	x_4 v y_2	X win by 1
x_1 v y_1	x_2 v y_4	x_3 v y_2	x_4 v y_3	Y win by 1
x_1 v y_1	x_2 v y_4	x_3 v y_3	x_4 v y_2	Draw
x_1 v y_2	x_2 v y_1	x_3 v y_3	x_4 v y_4	Draw
x_1 v y_2	x_2 v y_1	x_3 v y_4	x_4 v y_3	Draw
x_1 v y_2	x_2 v y_3	x_3 v y_1	x_4 v y_4	X win by 1
x_1 v y_2	x_2 v y_3	x_3 v y_4	x_4 v y_1	X win by 2
x_1 v y_2	x_2 v y_4	x_3 v y_1	x_4 v y_3	Draw
x_1 v y_2	x_2 v y_4	x_3 v y_3	x_4 v y_1	X win by 1
x_1 v y_3	x_2 v y_1	x_3 v y_2	x_4 v y_4	Y win by 1
x_1 v y_3	x_2 v y_1	x_3 v y_4	x_4 v y_2	Draw
x_1 v y_3	x_2 v y_2	x_3 v y_1	x_4 v y_4	Draw
x_1 v y_3	x_2 v y_2	x_3 v y_4	x_4 v y_1	X win by 1
x_1 v y_3	x_2 v y_4	x_3 v y_1	x_4 v y_2	Draw
x_1 v y_3	x_2 v y_4	x_3 v y_2	x_4 v y_1	Draw
x_1 v y_4	x_2 v y_1	x_3 v y_2	x_4 v y_3	Y win by 2
x_1 v y_4	x_2 v y_1	x_3 v y_3	x_4 v y_2	Y win by 1
x_1 v y_4	x_2 v y_2	x_3 v y_1	x_4 v y_3	Y win by 1
x_1 v y_4	x_2 v y_2	x_3 v y_3	x_4 v y_1	Draw
x_1 v y_4	x_2 v y_3	x_3 v y_1	x_4 v y_2	Draw
x_1 v y_4	x_2 v y_3	x_3 v y_2	x_4 v y_1	Draw

Of the 24 possible outcomes, side X wins by 2 units once and by 1 unit 4 times. The results are symmetrical with Y also winning by 2 units once, and by 1 unit 4 times, and the remaining 14 outcomes resulting in a draw.

However, if the same scenario is considered with an offset for Y of one unit (i.e. y_2, y_3, y_4, y_5), the outcomes are illustrated in Table 3. In this case, of the 24 possible outcomes, side X wins by 4 units once, by 3 units on 3 occasions, by 2 units on 11 occasions, by 1 unit on 7 occasions and 2 draws.

This single unit offset result could be summarised as either the mean number of wins (in this case 1.75 [42/24] in favour of side X) or as an average percentage of the engagements (in this case 43.75% [1.75*100/4] in favour of side X).

Table 3: 4v4 Engagement Outcomes With Single Offset.

Engagement 1	Engagement 2	Engagement 3	Engagement 4	Overall outcome
x_1 v y_2	x_2 v y_3	x_3 v y_4	x_4 v y_5	X wins by 4
x_1 v y_2	x_2 v y_3	x_3 v y_5	x_4 v y_4	X wins by 3
x_1 v y_2	x_2 v y_4	x_3 v y_3	x_4 v y_5	X wins by 3
x_1 v y_2	x_2 v y_4	x_3 v y_5	x_4 v y_3	X wins by 2
x_1 v y_2	x_2 v y_5	x_3 v y_3	x_4 v y_4	X wins by 2
x_1 v y_2	x_2 v y_5	x_3 v y_4	x_4 v y_3	X wins by 2
x_1 v y_3	x_2 v y_2	x_3 v y_4	x_4 v y_5	X wins by 3
x_1 v y_3	x_2 v y_2	x_3 v y_5	x_4 v y_4	X wins by 2
x_1 v y_3	x_2 v y_4	x_3 v y_2	x_4 v y_5	X wins by 2
x_1 v y_3	x_2 v y_4	x_3 v y_5	x_4 v y_2	X wins by 2
x_1 v y_3	x_2 v y_5	x_3 v y_2	x_4 v y_4	X wins by 1
x_1 v y_3	x_2 v y_5	x_3 v y_4	x_4 v y_2	X wins by 2
x_1 v y_4	x_2 v y_2	x_3 v y_3	x_4 v y_5	X wins by 2
x_1 v y_4	x_2 v y_2	x_3 v y_5	x_4 v y_3	X wins by 1
x_1 v y_4	x_2 v y_3	x_3 v y_2	x_4 v y_5	X wins by 2
x_1 v y_4	x_2 v y_3	x_3 v y_5	x_4 v y_2	X wins by 2
x_1 v y_4	x_2 v y_5	x_3 v y_2	x_4 v y_3	Draw
x_1 v y_4	x_2 v y_5	x_3 v y_3	x_4 v y_2	X wins by 1
x_1 v y_5	x_2 v y_2	x_3 v y_3	x_4 v y_4	X win by 1
x_1 v y_5	x_2 v y_2	x_3 v y_4	x_4 v y_3	X win by 1
x_1 v y_5	x_2 v y_3	x_3 v y_2	x_4 v y_4	X wins by 1
x_1 v y_5	x_2 v y_3	x_3 v y_4	x_4 v y_2	X wins by 2
x_1 v y_5	x_2 v y_4	x_3 v y_2	x_4 v y_3	Draw
x_1 v y_5	x_2 v y_4	x_3 v y_3	x_4 v y_2	X wins by 1

In order to quickly derive the combinations and overall outcomes a simple MicroSoft Excel spreadsheet simulation model was developed. The advantage of a simulation model approach was the flexibility to easily deal with ranked values taken from different overall population sizes and elements of equal rank values within the overall population size.

The effect of an offset for other scenarios will depend on the number of engagements being considered and is illustrated in Figure 5, which shows the average percentage of the engagements won by side X . The figure has been obtained from 1000 runs of the simulation for each engagement and offset. The example illustrated in Table 3 can be seen by selecting the “offset 1” line, locating the value of 4 from the “Number of Engagements” axis and reading the number of wins (43.75) from the “percentage wins” axis.

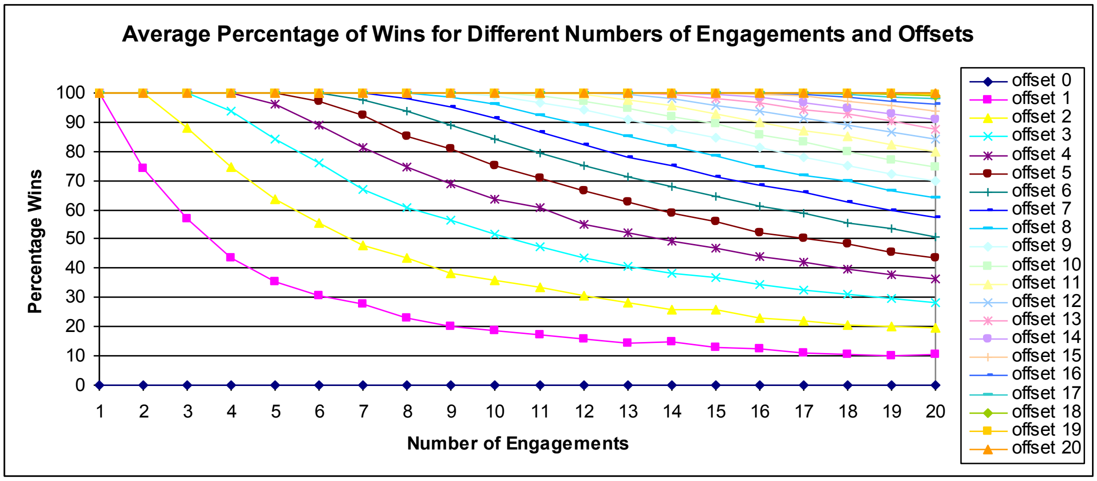

Figure 5: Average Percentage of Wins for Different Numbers of Engagements and Offsets.

Tables 2 and 3 illustrate how any offset can potentially significantly affect the average outcome of a small engagement. However even for larger numbers of engagements small offsets can still be significant. For example a single offset for 20 engagements (5% change) can have a 10% increase in average percentage number of overall wins, and when wins do occur they are often substantial.

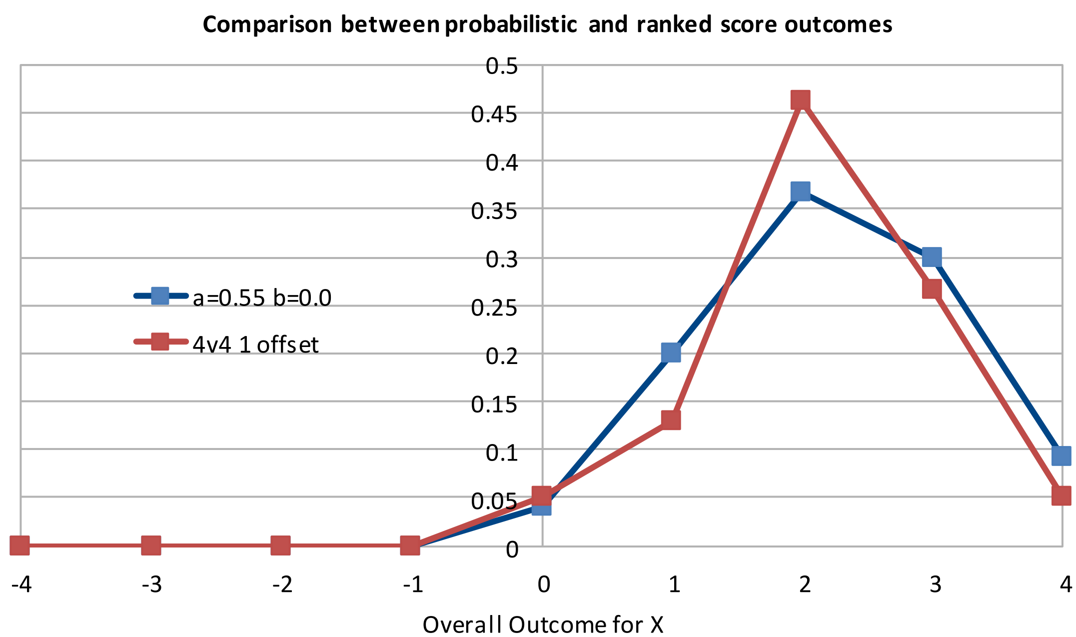

Figure 6: Comparison Between Probabilistic and Ranked Outcome Model.

6 DISCUSSION

By varying the model parameters (kill probabilities and ranking outcome rules) it is relatively easy to calibrate the probabilistic and ranked outcome models to produce similar overall results. For example Figure 6 illustrates that a ranked scoring method for a 4 v 4 engagement with a single offset (shown in Table 3) can give similar results to a probabilistic 4 v 4 engagement with $p_a = 0.55$ and for $p_b = 0.0$

(generated from the equations in Table 1). However the ranked outcome approach provides the flexibility to dynamically change the capability level of the participants as the air campaign progresses (for example to account for the decreasing USAF losses observed in Korea (Warnock 2000)), to incorporate factors such as tactical development and operational experience, without having to modify the key model parameters. Consequently the method has the potential to be able to incorporate time dependent factors such as new pilots joining an operational squadron, or the generation of "Aces" directly into an air combat simulation model. For example, by using a single offset but retaining a minimum rank (i.e. y_2, y_3, y_4, y_4), the 4 v 4 engagement of Table 4 would be obtained. This single unit offset with a minimum rank could be summarised as either the mean number of wins (in this case 1.5 [36/24] in favour of side X) or as an average percentage of the engagements (in this case 37.5% [1.5*100/4] in favour of side X).

Table 4: 4v4 Engagement Outcomes With Single Offset But Fixed Minimum

Engagement 1	Engagement 2	Engagement 3	Engagement 4	Overall outcome
x_1 v y_2	x_2 v y_3	x_3 v y_4	x_4 v y_4	X wins by 3
x_1 v y_2	x_2 v y_3	x_3 v y_4	x_4 v y_4	X wins by 3
x_1 v y_2	x_2 v y_4	x_3 v y_3	x_4 v y_4	X wins by 2
x_1 v y_2	x_2 v y_4	x_3 v y_4	x_4 v y_3	X wins by 2
x_1 v y_2	x_2 v y_4	x_3 v y_3	x_4 v y_4	X wins by 2
x_1 v y_2	x_2 v y_4	x_3 v y_4	x_4 v y_3	X wins by 2
x_1 v y_3	x_2 v y_2	x_3 v y_4	x_4 v y_4	X wins by 2
x_1 v y_3	x_2 v y_2	x_3 v y_4	x_4 v y_4	X wins by 2
x_1 v y_3	x_2 v y_4	x_3 v y_2	x_4 v y_4	X wins by 1
x_1 v y_3	x_2 v y_4	x_3 v y_4	x_4 v y_2	X wins by 2
x_1 v y_3	x_2 v y_4	x_3 v y_2	x_4 v y_4	X wins by 1
x_1 v y_3	x_2 v y_4	x_3 v y_4	x_4 v y_2	X wins by 2
x_1 v y_4	x_2 v y_2	x_3 v y_3	x_4 v y_4	X wins by 1
x_1 v y_4	x_2 v y_2	x_3 v y_4	x_4 v y_3	X wins by 1
x_1 v y_4	x_2 v y_3	x_3 v y_2	x_4 v y_4	X wins by 1
x_1 v y_4	x_2 v y_3	x_3 v y_4	x_4 v y_2	X wins by 2
x_1 v y_4	x_2 v y_4	x_3 v y_2	x_4 v y_3	Draw
x_1 v y_4	x_2 v y_4	x_3 v y_3	x_4 v y_2	X wins by 1
x_1 v y_4	x_2 v y_2	x_3 v y_3	x_4 v y_4	X wins by 1
x_1 v y_4	x_2 v y_2	x_3 v y_4	x_4 v y_3	X wins by 1
x_1 v y_4	x_2 v y_3	x_3 v y_2	x_4 v y_4	X wins by 1
x_1 v y_4	x_2 v y_3	x_3 v y_4	x_4 v y_2	X wins by 2
x_1 v y_4	x_2 v y_4	x_3 v y_2	x_4 v y_3	Draw
x_1 v y_4	x_2 v y_4	x_3 v y_3	x_4 v y_2	X wins by 1

The direct comparison between the results with and without the minimum rank (i.e. between Table 3 and Table 4) is shown in Figure 7, and illustrates how the variability in the results decreases when the minimum ranking constraint is introduced. The use of a minimum ranking constraint can be used to represent factors such as air crew experience and to facilitate the introduction of additional assets into the air campaign scenario. The most appropriate method for achieving this is an area that would require additional research.

7 SUMMARY

Aggregated computer simulation models of air-to-air combat invariably derive engagement outcomes using some form of "probability of kill" calculation. A ranked outcome approach is an alternative method which can be used to obtain the same effect within the combat model but providing the ability to directly incorporate variability such as combat experience gained during the campaign into the simulation. While the concept shows promise, further work is still needed to validate the method against historical analysis data

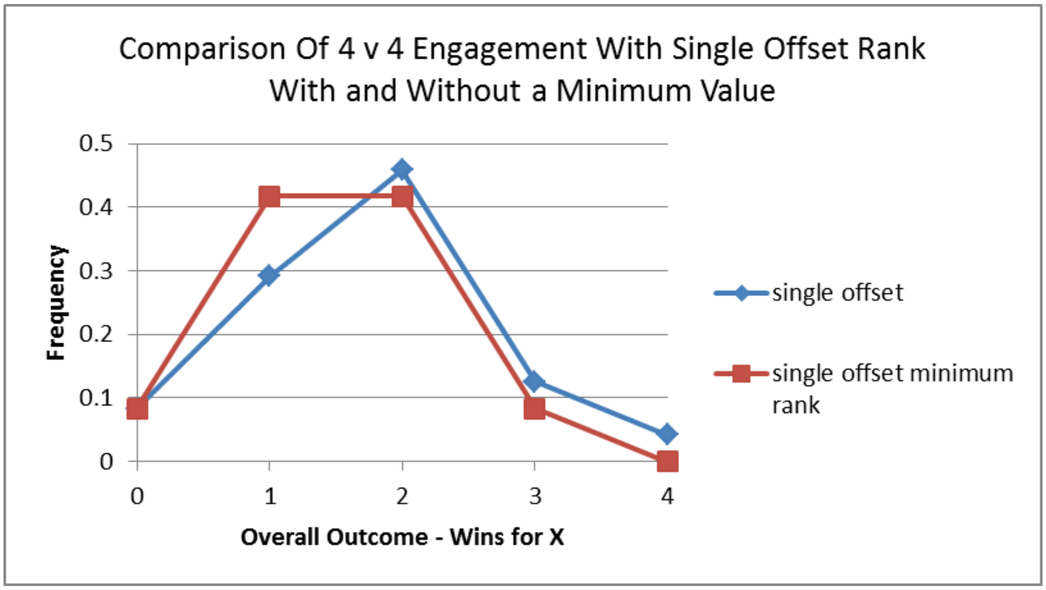

Figure 7: Comparison Of Single Offset Results With and Without a Minimum Value

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