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Multi-Method Approach to Future Army Sub-Concept Analysis

Fred DJ Bowden, Luke Finlay, Darren Lohmeyer and Colin Stanford

[1] *Land Operations Division, Defence Science and Technology Organisation*
Email: Luke.Finlay@dsto.defence.gov.au

Abstract: Recon Fires is a concept whereby military units manoeuvre on the battlespace to elicit a response from an unknown enemy. One key question about the implementation of this concept is: "how many Recon Fires missions can a generic unit perform before becoming operationally unviable?" To investigate this, a multi-method approach combining seminar wargaming, closed-loop simulation and Markov modelling and analysis was used.

Previous studies that have taken a similar approach generally conclude with statistical analysis of the data from the closed-loop simulation. An advantage of taking the additional step of generating a Markov Chain was that only a single typical Recon Fires Mission needed to be modelled, reducing the time to develop the closed-loop simulation model. This in turn gave quicker turn-around on results and allowed greater exploration of "what if" situations.

The seminar wargame allowed the Recon Fires aspects to be isolated from the broader operation and gave initial insights into the concept. It also provided the key data required to construct a closed-loop simulation. The closed-loop simulation was then run multiple times for different starting states. Each starting state represented a different strength of the force before it began a Recon Fires mission. The generated data was analysed directly and used to construct the Markov Chain. The Markov Chain was then analysed to find the mean time until the generic unit became operationally unviable.

Keywords: *Concept Analysis, Wargaming, Closed-Loop Simulation, Markov Chain*

1. INTRODUCTION

The Australian Army has endorsed Adaptive Campaigning (Australian Army (2006)) as its new concept of operations to meet the challenges of the future. A key aspect of Adaptive Campaigning is the sub-concept Recon-Fires. The Recon-Fires sub-concept can be expressed as the following three steps being repeated on the battlespace:

1. Manoeuvre to force the enemy above the discrimination threshold[1],
2. Hold the enemy above the discrimination threshold,
3. Use joint fires and organic firepower to neutralise the enemy.

An operation or mission using the Recon-Fires concept ends when the enemy either drops below the discrimination threshold or is neutralised. It is recognised that such manoeuvres are an inherently dangerous activity, but they fit into the context of accomplishing the Army's mission while minimising overall casualties. The main focus of this paper is in answering the key question which needed to be addressed as part of this sub-concept: "How many times can a Combined Arms Team (CAT) conduct Recon-Fires missions?"

To address this question a multi-method approach involving three steps with three different analytical methods was used: seminar wargaming (Coutts and Dexter (2008) and James and Coutts (2005)), closed-loop simulation (Matsumura *et al.* (2000), Matsumura *et al.* (2004) and Steeb *et al.* (2004)) and mathematical modelling (Finn and Kent (1985), Larson and Kent (1994) and Taylor (1983)). First a Limited Objective Experiment (LOE) was held to conduct a seminar wargame. This allowed the data required for the closed-loop simulation model to be captured. The closed-loop simulation model was then run multiple times in a model-test-model process to refine the model (Brennan *et al.* (2001), Davis *et al.* (1999) and TTCP (2006)). The data from the closed-loop simulation was used to generate the Markov Chain model. This model also went through the model-test-model process to refine it. Findings from the Markov chain also fed back into additional iterations of the closed-loop simulation, further refining it. The results from the Markov chain were then used to calculate the number of Recon-Fires missions that can be performed. The overall analytical approach is shown in Figure 1.

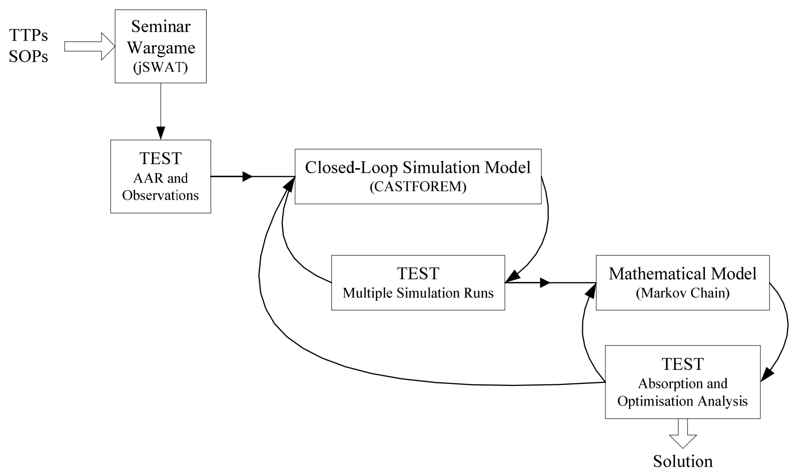

Figure 1. Recon-Fires Analysis Approach

The approach taken differed from existing techniques by the combination of methods and the way these methods were combined. The approach is similar to that of the close combat study in Bowley *et al.* (2004), however, takes the additional step beyond the closed-loop simulation by the construct of a Markov chain model. It also relates to the work done in Bender *et al.* (2006) where wargaming fed a spread sheet model. However, in this study, instead of using a spread sheet model a Markov chain model was built and the additional closed-loop simulation step was added. The use of Markov models to look at military strategies was used by Garrambone *et al*. (1994) and Menq *et al.* (2006). In these cases a simple Markov model was used to validate a more detailed simulation in a similar way that the Lanchester equations were used in Bowley *et al.* (2004) and Bowley *et al.* (2003) to validate the Close Action Environment (CAEn). In our analysis, we used Markov chains (the mathematical model) as the final analysis tool to link the results from the closed-loop simulation into combined probability paths through the transition states as force strength degraded.

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[1] The discrimination threshold can be thought of as the event horizon at which an enemy element can be identified.

This paper first outlines the methodology used to perform the analysis. Next it provides some indicative results to illustrate how the methodology can be applied in practice. Finally it discusses some future work and insights gained from the approach.

2. METHODOLOGY

The focus of this paper can be rephrased as the problem: "Determine the number of times that a CAT can conduct Recon-Fires missions before it is no longer operationally viable[2]". This problem has two key features:

1. The problem was focused on stopping criteria
2. The key variable in determining the outcome of each Recon-Fires mission is the CAT strength. So, the states of the model are the possible strength levels of the CAT. This means the successive Recon-Fires missions conducted by the CAT can be treated as discrete events, where each state represents the force strength of the CAT and transitions between the states are determined by the possible losses taken by the CAT. Thus the system can be analysed as a stochastic discrete event process.

Also, under the Recon-Fires mission definition, each mission can be assumed to be unique from any other. The justification for this assumption is that each Recon-Fires mission has the same learning effect for both sides and each mission involves different tactics by the enemy, reducing any learning. If this assumption does not hold then the value calculated would be a worse case example as the learning effects of multiple missions would result in less casualties for the CAT. This means that the entities involved in each Recon-Fires mission can be considered to have no memory of any previous mission. So a series of Recon-Fires missions can be represented by a single generic mission provided the CAT does not remember any previous missions. Due to the memoryless nature of the events the overall process is Markovian. This allowed successive Recon-Fires missions conducted by the CAT to be modelled as a discrete Markov chain that has a number of absorbing states that represent when the CAT is no longer operationally viable.

This raised the issue of how to generate the states and transition probabilities for the discrete Markov chain. One option would have been to use seminar and human-in-the-loop wargames and simulations[3], however, this would be very resource intensive in terms of participants and time. Also, as expressed in Bowley (1999), both of these methods have repeatability issues due to variance in the human decision makers; both can also be affected by learning effects. The alternative was to use a closed-loop simulation, which would be able to provide statistically significant data.

To construct a model of a typical Recon-Fires mission in the closed-loop simulation required identification of the planning information (including the Scheme of Manoeuvre) as well as relevant Techniques, Tactics and Procedures (TTPs). To get this information a seminar wargame was conducted. This approach not only allowed the required data to be captured but also allowed the plan to be tested before it was modelled in the closed-loop simulation.

An alternative approach to examining new concepts is to use wargaming tools as done in Matsumura *et al.* (2000), Grossman *et al*. (2002) and Matsumura *et al.* (2004). For the Recon-Fires question to be addressed in this way would have required representing a series of sequential Recon-Fires missions in a wargaming tool. A CAT would then work its way through the sequence of missions until it was no longer operationally viable. To be statistically confident in the results, such a wargame would need to run many times. For reasons mentioned earlier, both seminar wargaming and human-in-the-loop simulations are not appropriate tools for this. Thus, this approach would need to be modelled in a closed-loop simulation. The use of a closed-loop simulation also has a number of drawbacks. Firstly, the scenario would need to be sufficiently demanding to ensure that the CAT would eventually be reduced to an operationally unviable state; otherwise only a lower bound would have been calculated. Additionally, the decision logic for the closed-loop simulation would also need to handle re-forming and re-grouping elements within the CAT during the Recon-Fires mission – such decision logic is generally complex. So although it was possible it would require a lot of time to set up.

Thus, the approach taken is similar to traditional approaches where seminar wargames or human in the loop simulations feed closed-loop simulations. In these cases statistical tools are used to analyse the data from the closed-loop simulation to determine the outcome of the study. However, due to the nature of the problem

[2] In this study a CAT was considered to be operationally viable if it could conduct a Recon-Fires mission without re-enforcement.

[3] Examples of human-in-the-loop wargames and simulations include Janus, OneSAF Objective Systems, CAEn and JCATS. References on these types of tools include USJFCOM (2008), Steeb *et al.* (2004), Williams *et al.* (2006), Coutts and Dexter (2008), Coutts *et al.* (2008), Gaertner (2004) and Bender *et al.* (2006).

being addressed here, this data has been used to develop a Markov chain model. This means only a small part of the battlefield, a single typical Recon Fires Mission, had to be modelled, reducing the time required to develop the closed-loop simulation model which is normally the most time consuming step in this type of analysis. This in turn gave a quicker turn around of results and allow more "what if?" situations to be considered.

2.1. Seminar Wargame

The main outcome of the seminar wargame was to develop an understanding of how a Recon-Fires mission would be conducted by Army. This understanding allowed development of a Recon-Fires mission that could be modelled within the closed-loop simulation. To address this, Army developed some basic procedures outlining how a Recon-Fires mission might be conducted. These procedures then needed to be tested to explore the impact of their implementation and possible alternative approaches. Given the potential breadth of exploration, the seminar wargaming approach (James and Coutts (2005)) was considered most appropriate as it allows greater exploration of ideas (Bowley (1999), Millikan *et al.* (2005) and Menadue *et al.* (2009)).

In this particular case the seminar wargame was conducted as a single blind (Menadue *et al.* (2009)) or one player game (Perla (1990)). In this type of wargaming the elements being exercised are only provided with the information available to them while the other actors in the game, including the opposing force, have a god's eye view. Essentially these other players are considered to be part of exercise control, although in this case the opposing force developed its initial plan independently.

A series of battlegroup seminar wargames were run using jSWAT (Menadue *et al.* (2009)) where CATs within the battlegroup were forced to conduct Recon-Fires missions. From this broader context a typical Recon-Fires mission was identified to be modelled. The mission selected was generic in nature and represented a typical Recon-Fires mission. This approach also meant that the mission modelled took into account the complete battlegroup situation, ensuring what was modelled was a realistic sub-portion of the overall plan. The seminar wargames were followed up by an AAR (Darling *et al.* (2005)) to explore, among other issues, the success of the procedures used.

By conducting the exploration, and to a lesser extent an initial test, of the concept in this way, a more robust plan and TTPs were developed. This was principally due to three factors. First the presence of an enemy independent of the force being tested allowed stresses to be placed on the concept which were less likely to be present in a simple planning activity. It also tested the ability of the concept in changing circumstances. The second factor related to the fact that seminar nature of the approach encouraged all sides to discuss the concept in terms of positive and negative aspects. For the LOE, these discussions were formally conducted as part of a series of AARs. However, the seminar structure allowed the exploration and discussion to occur throughout the wargaming process. Finally as discussed earlier, it allowed the isolation of a typical Recon Fires mission as part of the broader operation providing initial insights into the concept.

There were additional conceptual gains from this process including a better understanding of the Recon-Fires sub-concept and how Army could conduct it.

2.2. Closed-Loop Simulation

Having captured the data needed to model a typical Recon-Fires mission, a closed-loop simulation was developed in the Combined Arms Support Task Force Evaluation Model (CASTFOREM) (TRADOC (2005)).

Before running the closed-loop simulation, there was a need to determine which CAT force structures needed to be used as starting states in the simulation[4]. To do this all the possible operationally viable and unviable states were considered. A CAT consists of a number of soldiers, tanks and infantry fighting vehicles (IFVs). Define $S_S(t)$, $S_T(t)$ and $S_I(t)$ as the number of soldiers, tanks and IFVs respectively at time t. The initial sizes of the force are defined as $S_S(t)=S_{max}$, $S_T(t)=T_{max}$ and $S_I(t)=I_{max}$. To be in an operationally viable state, all three variables need to be greater than or equal to S_{min}, I_{min} and T_{min} respectively[5]. The set of states are defined as

$$S = \{(S_S, S_T, S_I) : 0 \le S_S \le S_{\max}, 0 \le S_T \le T_{\max}, 0 \le S_I \le I_{\max}\}$$

[4] As discussed earlier the enemy and environment remained constant for each starting state.

[5] In this definition of the absorbing states each type of unit has been considered independently based on subject matter advice. The method in general allows absorbing states to be defined however required.

where S_S, S_T and S_I represent the quantities of soldiers, tanks and IFVs respectively. The total number of states is equal to $|S| = (S_{\max}+1)(T_{\max}+1)(I_{\max}+1)$. Also define the set of operationally viable states as

$$B = \{(B_S, B_T, B_I) : S_{\min} \le B_S \le S_{\max}, T_{\min} \le B_T \le T_{\max}, I_{\min} \le B_I \le I_{\max}\} \subset S .$$

The set of absorbing or operationally unviable states is defined as $\kappa = S \backslash B$. The set B contains $|B| = (S_{\max} - S_{\min} + 1)(T_{\max} - T_{\min} + 1)(I_{\max} - I_{\min} + 1)$ states and the set κ contains $|\kappa| = |S| - |B|$ states. Defining the possible states in this way is similar to the approach taken in Menq and Chang (1993). However, where the states used by Menq and Chang (1993) represented the strength of both forces, here only the CAT strength is represented.

The number of CASTFOREM Monte Carlo runs necessary to obtain the required level of statistical significance in the transition probabilities also needed to be calculated. Based on the technique described in Anderson and Goodman (1957) and Craig and Sendi (2002), 400 simulation runs for each operationally viable state were required to ensure a transition probability accuracy of at least 0.0075 within a 95% confidence interval.

2.3. Markov Chain

Having determined all the possible states and run the closed-loop simulation for each of the operationally viable states the next step was to generate the Markov chain transition probabilities. To do this, let K be the number of CASTFOREM runs required and the total number of states be h. Also, define the count matrix:

$$N = \begin{pmatrix} n_{11} & n_{12} & \cdots & n_{1h} \\ n_{21} & n_{22} & \cdots & n_{2h} \\ \vdots & \vdots & \vdots & \vdots \\ n_{h1} & n_{h2} & \cdots & n_{hh} \end{pmatrix},$$

where n_{rc} was the number of CASTFOREM simulations where state r moved to state c. CASTFOREM was run only on operationally viable rows. For the operationally unviable rows, the row is defined as having all elements equal to 0 except n_{rr} which is defined as K, as these rows correspond to states that are absorbing states. Note that the sum $\sum_{r=1}^{h} n_{rc} = K$ for all integer values of $c \in [1, h]$. Given the observed count matrix, the maximum likelihood estimate of the transition matrix is simply the row proportions of N, defined as

$$\hat{P} = \{\hat{\theta}\} \text{ where } \hat{\theta} = \frac{n_{rc}}{\sum_{r=1}^{h} n_{rc}} = \frac{n_{rc}}{K} \text{ for all } r \text{ and } c \in [1, h].$$

To determine how many Recon-Fires missions a CAT can conduct before becoming operationally unviable the mean time to absorption must be calculated. Under the assumption that each non-absorbing state is absorbed the mean absorption time $(t_i)_{i \in B}$ as the minimal non-negative solution to the equations:

$$t_i = 1 + \sum_{j \in B} \hat{p}_{ij} t_j$$

where $\hat{p}_{ij}$ are the elements in the matrix $\hat{P}$ (Bowden (2001)).

In defining the Markov chain it is possible to have one single absorbing operationally unviable state if we were only interested in the mean absorption time which would make the Markov Chain simpler. However, modelling all of the absorbing states provides insights into the reasons for becoming operationally unviable.

3. INDICATIVE RESULTS

The largest model considered so far contained 500 states of which 54 were operationally viable. However, here only a simple example will be used to illustrate the types of results generated by this methodology. Consider the case when S_{min}=2, T_{min}=1, I_{min}=0, S_{max}=3, T_{max}=1 and I_{max}=1. That is, the CAT has a starting strength of 3 soldiers, 1 tanks and 1 IFV and to be operationally viable the CAT needs at least 2 soldiers and 1 tank. The set S contains 16 states of which 4 are operationally viable. Assume a closed-loop simulation was run over the 4 operationally viable states and the transition matrix in Figure 2 resulted.

Using this matrix the mean time until absorption can be calculated for all the operationally viable states (the set B). For the initial full force state of 3 soldiers, 1 tank and 1 IFV, $t_{(3,1,1)} \approx 3.68$, meaning that, on average, about 3.68 recon-fires missions could be performed before becoming operationally unviable. The mean time to absorption is also calculated for the other 3 operationally viable states as $t_{(2,1,1)}=2.5$, $t_{(3,1,0)} \approx 2.264$ and $t_{(2,1,0)}=2$.

$$\hat{P} = \begin{array}{c} (3,1,1) \\ (2,1,1) \\ \\ \\ \\ \\ \\ \\ (3,1,0) \\ (2,1,0) \\ \\ \\ \\ \\ \\ \\ \end{array} \begin{pmatrix} 0.5 & 0.25 & 0 & 0 & 0.1 & 0.05 & 0 & 0 & 0.05 & 0.05 & 0 & 0 & 0 & 0 & 0 & 0 \\ & 0.6 & 0.05 & 0.05 & 0 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & & & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & & & & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ & & & & & & & & 0.47 & 0.1 & 0.1 & 0.1 & 0.1 & 0.1 & 0.01 & 0.02 \\ & & & & & & & & & 0.5 & 0.1 & 0.1 & 0 & 0.1 & 0.1 & 0.1 \\ & & & & & & & & & & 1 & 0 & 0 & 0 & 0 & 0 \\ & & & & & & & & & & & 1 & 0 & 0 & 0 & 0 \\ & & & & & & & & & & & & 1 & 0 & 0 & 0 \\ & & & & & & & & & & & & & 1 & 0 & 0 \\ & & & & & & & & & & & & & & 1 & 0 \\ & & & & & & & & & & & & & & & 1 \end{pmatrix}$$

Figure 2. Indicative Transition Probability Matrix

Using the Markov chain starting at the initial state (3,1,1), the equilibrium Markov distribution can be calculated and, therefore, the reason for becoming operationally unviable. The probability of being absorbed due to a loss of soldiers alone was 0.21. For tank loss alone, the probability was 0.49 and for both soldier loss and tank loss combined the probability was 0.30. From this it was clear that the loss of the tank was the most likely reason for the CAT to become operationally unviable. This gives the initial starting point for considering how the performance of the CAT can be increased. As an initial step the Markov chain transition probabilities can be varied to determine the impact. Thus the variation with the biggest impact can then be transferred to the closed-loop simulation to determine how this change can be achieved.

4. DISCUSSION/CONCLUSIONS

In this paper we have presented a successful mixed method approach to study the Army sub-concept of Recon-Fires. The method involved the combination of seminar wargaming, closed-loop simulation and Markov chain analysis. By combining these three recognised techniques the problem state was not only analysed but also get better insight into how the concept as a whole worked. For example, as part of the seminar wargaming process provided a better understanding of the TTPs used to bring and keep enemy above the discrimination threshold. Also as part of the closed-loop simulation trade offs between protection, response time and fire power, as discussed in James *et al.* (2007), can also be considered. So each of these steps not only allowed the building of the Markov chain but also provided further understanding of how this concept can be implemented. Although not discussed in detail here, additional work is also being done to extend the Markov chain to a Markov decision process to allowing the optimal re-enforcement strategy to maximise the time before the CAT becomes operationally unviable to be calculated. One final area of analysis that still needs to be conducted is a sensitivity analysis in terms of the enemy, terrain and possibly the Recon-Fires TTPs used.

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