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A Hybrid Simulation Model for Preparedness

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Abstract: Defence allocates considerable resources to maintain preparedness. Preparedness is the capacity of defence to sustainably provide forces that are able to accomplish government-directed tasks. Defence Preparedness Requirements plans are produced every year and agreed upon by the chiefs of services. Each service commits to deliver Defence Elements to perform specific military roles in certain numbers and at certain readiness notices. In light of this, the question arises: how well do these preparedness plans perform in reality? That is to say, how well prepared are we to perform disaster relief operations, military conflicts, and other operations, within reasonable warning times? In order to address this question, a non-linear dynamic probabilistic model of preparedness called DyPSim, has been developed and implemented in Java. DyPSim is a hybrid simulation model that quantitatively determines Defence Element availability for a given force structure subject to the demands of a series of military operations. We have employed the concept of supply and demand to model the preparation of Defence Elements for deployment, and their subsequent deployment on military operations. DyPSim combines continuous processes described by differential equations (the supply model) with stochastic discrete events (the demand model). We present the results of running an unclassified dataset through the model for verification purposes.

The system performance metric has been defined as the ratio of successful events divided by failed events to the total number of events during the simulation period. Events are judged to be successful or failed on the basis of their level of resourcing and the timeliness of the resourcing. System success as a percentage was measured by the number of successful events during 30 years of simulation time compared to the total number of events over this period and averaged out over 30 simulation runs. The system failure rate was measured in an equivalent manner. A tipping point can be seen in Figure A1 above which the number of failed events will exceed the number of successful events. Lack of resources in the appropriate time frames due to the spread of resources across different events will cause more failures than successes. We now have two ways to assess the performance of a force structure: we can monitor the success or failure of key events, and we can monitor the system failure to success ratio. Figure A2 shows the success and failure trend as a function of the number of concurrent events. The obtained results demonstrate force structure suitability as a function of the concurrent event profile in the context of preparedness requirements.

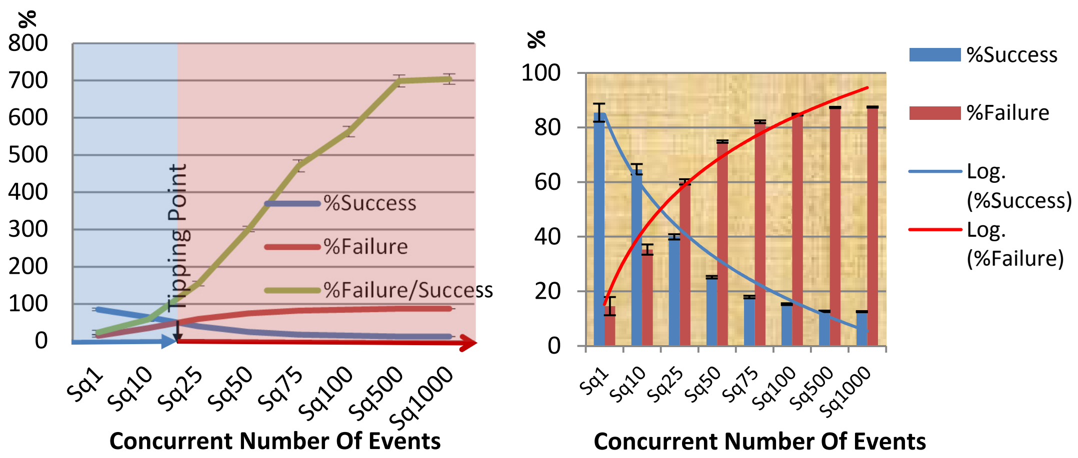

Figure A1 (left) & Figure A2 (right)

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1. INTRODUCTION

The Australian Defence Organisation (ADO) periodically conducts whole of force planning activities such as the Force Structure Review, which we shall refer to as episodic reviews. The purpose of these episodic reviews is to assess the appropriateness of the planned future force against plausible future contingencies, which we shall refer to as vignettes. In order to conduct an episodic review, a range of future Defence Elements (e.g. the Joint Strike Fighter) and their associated preparedness levels need to be considered under the constraint of indicative ranges of strategic warning time and limited financial resources.

The preparedness concept describes Defence's preparation to undertake military operations, and comprises three key components - how ready we are for the task (**readiness**), how long the force has to get ready (**warning time**), and how well we can sustain the effort once committed (**sustainability**). Defence Preparedness Requirements (DPR) plans refined on an annual basis by the chiefs of the services define numbers and readiness level for all capabilities as the means by which preparedness is ensured.

To date the episodic reviews have relied on manual planning processes to determine Defence Element availability in order to focus efforts on assessing the suitability of Defence Element mixes against the vignette set. We propose to use a hybrid simulation model to quantitatively determine Defence Element availability in order to support a more rigorous assessment of the suitability of Defence Element numbers and associated preparedness settings. We use the concept of supply and demand to model the preparation of Defence Elements for deployment, and their subsequent deployment on military operations. Towards this goal, we present indicative modelling results for an unclassified force structure and DPR.

2. MODEL

In order to investigate the fitness of force structure and DPR options, a hybrid simulation model has been constructed. The model is based on the concept of supply and demand. The supply part is represented by the Defence Elements available or being available in the future, expressed in preparedness terms. The demand part is modelled by generated events. Associated with events are the requested resources. The required resources for these events are based on historical data or hypothetical future vignettes.

Preparedness levels are in a constant state of change, while events occur at discrete time points. The supply part is changing continuously on each simulation step, while the demand part is requesting resources discretely. This suggests the need for a hybrid modelling approach (Nutaro, 2011).

2.1. Supply Model

The supply model covers several aspects of preparedness such as personnel competency and platform availability which is affected by maintenance and deficiency. Our model uses statistical distributions to model maintenance and deficiency but personnel competency is modeled by the knowledge acquisition process.

The fundamental equation for knowledge acquisition is derived from the so-called 'ACT-R model' (Anderson and Schunn, 2000). It encapsulates the power law of practice, the power law of forgetting and the multiplicative effects of practice and retention. The general expression formulated by Anderson and Schunn (2000) is as follows:

$$\alpha = AN^c t^{-d} \qquad (1)$$

where:

- A is a constant (scaling factor)
- N is the amount of practice
- t is time
- c is the rate of learning
- d is the rate of decay.

Model of Learning

The first part of the Anderson and Schunn model:

$$AN^c t^{-d} \qquad (2)$$

can be substituted by the following differential equation with the initial condition of the decayed skill and the time when the transition from decaying to training takes place:

$$c\frac{d\alpha(t)}{dt} + \alpha(t) = KNu(t) \qquad (3)$$

where:

$\alpha(t)$ is the skill level during learning.

$\alpha(t_0) = \beta(t_0)$ is the initial condition for the first order differential equation for time t_o.

K is the knowledge gain.

u(t) is the step function.

The analytical solution is as follows:

$$\alpha(t) = \beta(t_0)e^{-\frac{1}{c}(t-t_o)} + (1-e^{-\frac{1}{c}(t-t_o)})KN \qquad (4)$$

where:

c > 0 is the learning rate, as in the ACT-R model.

$\beta(t_o)$ is the level of decayed skill when the learning process starts.

N is the amplitude of the step function and is usually equal to 1.

For a full explanation of the model, please see forthcoming paper by Jagiello and Papacek (2015).

Model of Decay

The second part of the Anderson and Schunn model:

$$t^{-d} \qquad (5)$$

can be replaced by the following differential equation with the initial condition of the learned skills and the time when the transition from training to decaying takes place:

$$d * \frac{d\beta(t)}{dt} + \beta(t) = \varepsilon \qquad (6)$$

Where ε is the asymptote value of decay function, and where the initial conditions are:

$\beta(t_0) = \alpha(t_0)$,

$\beta(t)$ - is the skill level during decay.

The analytical solution is as follows:

$$\beta(t) = \alpha(t_0)e^{-\frac{1}{d}(t-t_o)} + \varepsilon(1-e^{-\frac{1}{d}(t-t_o)}) \qquad (7)$$

For a full explanation of the model, please see forthcoming paper by Jagiello and Papacek (2015).

2.2. Demand Model

The demand model is based on the force generation cycle as a single-server queuing system supplying services to incoming events. Incoming events are stored in a prioritised input queue and matched against available resources in the supply model. If the system has enough resources to satisfy requirements, then an event is passed on to the next queue. Otherwise an event is held in the input queue until either resources become available, or the event expires.

2.3. Model Structure

On each simulation step, one or more events may be generated. An event is associated with a particular vignette. The vignette defines the requirements for that event. Associated with each event are attributes such as the requested Defence Elements, their roles, quantities, readiness notices, event start time, duration, location and priority. An event type can be 'synchronised', in which Defence Elements must be deployed together, or 'asynchron', in which this requirement does not apply. Each event 'travels' through the system from one queue to another based on the attributes of that event, and available resources.

The model queues are outlined below:

- **Input Queue**: all incoming events.
- **Workup Queue**: events that have reached the workup stage.
- **Deployment Queue**: events that are ready to be deployed.
- **Travel to Theatre Queue**: events that have been dispatched to the theatre.
- **Theatre Queue**: events that are now at the theatre and are ready to be engaged.
- **Engagement Queue**: events that are currently engaged.
- **Disengagement Queue**: events are moved to the disengagement queue after the end of the event.
- **Travel to Base Queue**: events are moved to the 'travel to the base' queue after having completed the disengagement process.
- **Reconstitution Queue**: events which are in the process of reconstitution, i.e. recovering in preparation for a return to the pool of available resources.

The model generates events with requirements for resources. Based on these requirements, the effective number of Defence Elements is calculated, taking into account the relationship between preparedness numbers, roles and preparedness levels. These requirements are matched with the existing pool of available resources (Defence Elements) such that events can effectively acquire these Defence Elements. This process takes place in the input queue. When the event's requirements are met, the event is moved to the workup queue where its current level of preparedness will be raised to the operational level of capability.

When an event's Defence Elements reach the required preparedness level, the event either remains in the deployment queue until all Defence Elements reach the required preparedness level (for synchronized events) or the event is immediately moved to the travel to theatre queue (for asynchronised events).

Based on the distance and the speed of Defence Elements, the event will at some point in time reach the theatre queue. The event's start time attribute then determines when the event is moved from the theatre queue to the engagement queue. The event's end time attribute determines when the event is moved from the engagement queue to the disengagement queue. The event remains there for some time to recover from the engagement.

At the end of recovery period, events are placed in the travel to base queue. Based on the distance and speed, the event will at some point arrive at the base and is then placed in the reconstitution queue. After reconstitution, the event is removed from the reconstitution queue, recorded in the database for future analysis, and all Defence Elements are returned back to the pool of available resources.

There are three types of events:

- deployment event,
- rotation event,
- redeployment event.

Regular 'deployment' type events are the standard means by which Defence Elements are deployed on operations.

Rotation events are created when Defence Elements are due for rotation. Reinforcements are sent to the event, then, after a handover period, Defence Elements currently participating in the event return to their bases.

A redeployment event is created when Defence Elements are allocated to a new event from an existing event, rather than from their bases. For this to occur, the existing event must be in the disengagement queue, and within a given distance to the new event.

3. SIMULATION MODEL COMPONENTS

Our model has two major components:

- a Simulation Engine,
- and a Simulation GUI.

3.1. Simulation Engine

The simulation engine is the core of our simulator. It drives the simulation loop and advances the simulation time. For each simulation loop, it calculates the position and preparedness for all Defence Elements in the system. As events are generated, they are accepted or rejected based on the limitations of the simulated system. If an event is accepted, its start time is calculated in relation to the most recent event of the same type, and it is placed in the input queue. The input queue is sorted by the arrival time of intelligence. This is the time at which information on an upcoming event becomes available.

There are two system parameters that affect the acceptance or rejection of generated events: the total system capacity and the input queue capacity. If an incoming event cannot be accepted due to the system capacity limit, but has a higher priority than one or more events currently in the input queue, it will replace the lowest-priority event.

Events which linger for too long in the input queue without obtaining the required resources will expire and be removed from the system. Events which secured resources in the input queue are moved between the queues based on their internal parameters such as location, start of event, duration, etc.

3.2. Simulation GUI

The Simulation GUI (Graphical User Interface) gives a high-level view of the current state of the system, including both supply and demand models.

Figure 1 shows the GUI during simulation. It can be seen that the GUI is divided horizontally into three main sections. Each section relates broadly to a particular aspect of the simulation. At the very top is a toolbar for interacting with the simulator.

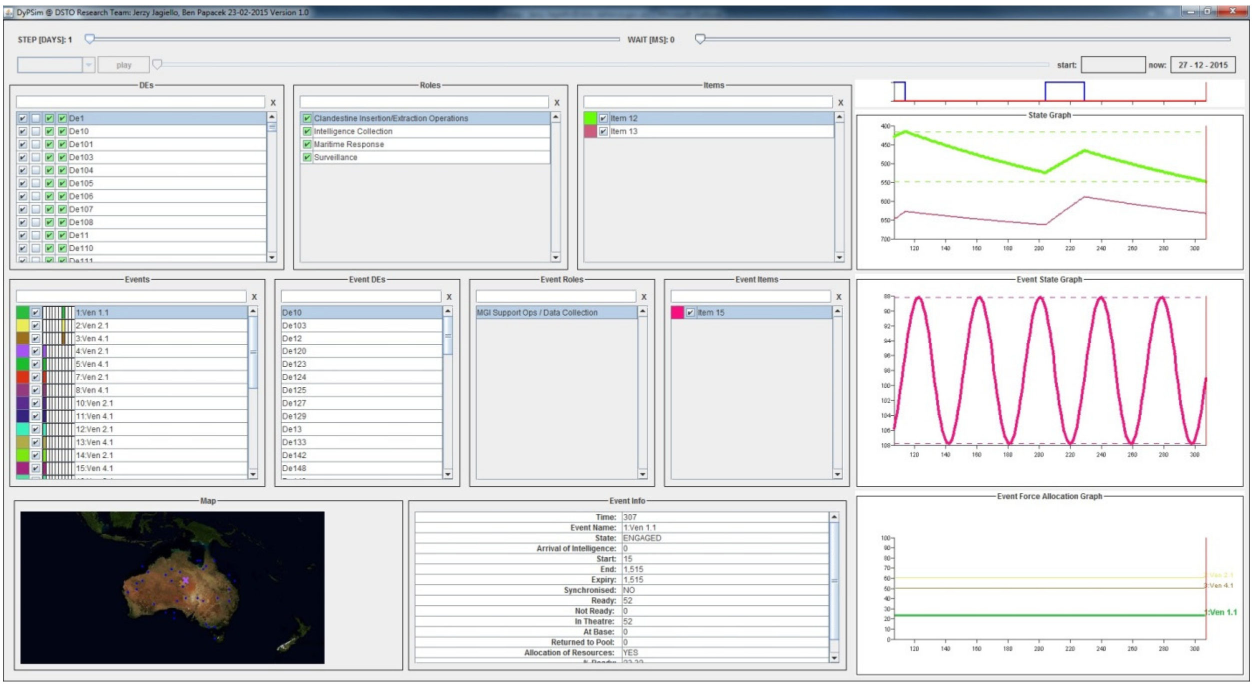


Figure 1. The Graphical User Interface

The top section relates to the supply model. It shows the preparedness of Defence Elements currently in the pool of resources. There are three tables to the left of a graph. The tables show - from left to right - Defence Elements, Roles and Preparedness Levels. The graph shows the current preparedness levels for each role.

The middle section is similar in function to the top section, but relates to the demand model, in that it shows forces currently allocated to events. The four tables show - from left to right - Events, Defence Elements, Roles and Preparedness Levels. Again, the graph shows current preparedness levels for each role selected in the tables.

The bottom section shows more information relating to events. The world map at the left shows the locations of forces and events. The table in the middle gives more detailed information on the currently selected event.

The graph at the right gives a timeline and visualisation of the forces contributing to each event currently underway.

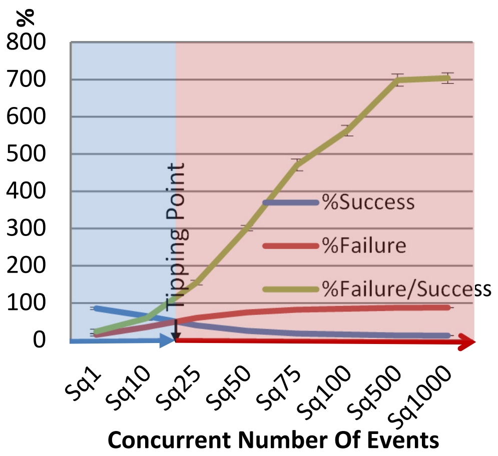
4. VERIFICATION

To verify modelling assumptions a series of experiments were conducted using an unclassified data set. The model was populated with DPR plans represented in tabular form. These preparedness plans encompass the force element availability and proficiency levels. Independently, research results of collective learning and skill retention in the Canadian Defence Force by Barbara et al. (2003), the US Army Research Institute by Macpherson et al. (1989), and the Naval Postgraduate School in Monterey California by MacKinnon et al. (2006) were incorporated into our model. The demand side of the dataset consists of a pool of predefined events with associated force element requests, duration, and some statistical parameters to influence the probability of event generation.

Behavior of the model was analysed from a concurrency point of view. For each number of concurrent events in the system (as an independent variable) 30 simulation experiments were executed to ensure statistical significance. Each simulation run covers a 30 year period. The simulation results were analysed by using SQL scripts and then statistical analysis was performed. A single factor ANOVA (significance level α = 0.05) was employed to test the null hypothesis that there is no difference between the means of the response variables for all different numbers of concurrent events trialed. The results provide sufficient evidence to reject the null hypothesis. The alternative hypothesis that results are due to the variability of an independent variable (number of concurrent events in the system) is justifiable.

5. RESULTS

The performance metric has been defined as the ratio of successful events divided by failed events to the total number of events during the simulation period. Events are judged to be successful or failed on the basis of their level of resourcing and the timeliness of the resourcing. System success as a percentage was measured by the number of successful events during 30 years of simulation time compared to the total number of events over this period and averaged out over 30 simulation runs. The system failure rate was measured in an equivalent manner.



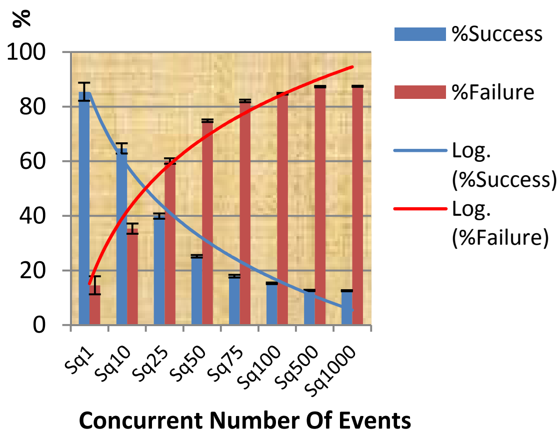


Figure 2. (left): System Failure to Success Ratio, **Figure 3.** (right): System Success and Failure Rates

Figure 2 clearly demonstrates that there is a point above which the number of failed events will exceed the number of successful events. Lack of resources in the appropriate time frames due to the spread of resources across different events will cause more failures than successes. We now have two ways to assess the performance of a force structure: we can monitor the success or failure of key events, and we can monitor the system failure to success ratio. Figure 3 shows the success and failure trend as a function of the number of concurrent events.

Individual performance of Defence Elements as a function of the number of concurrent events in the system is presented in Figure 4.

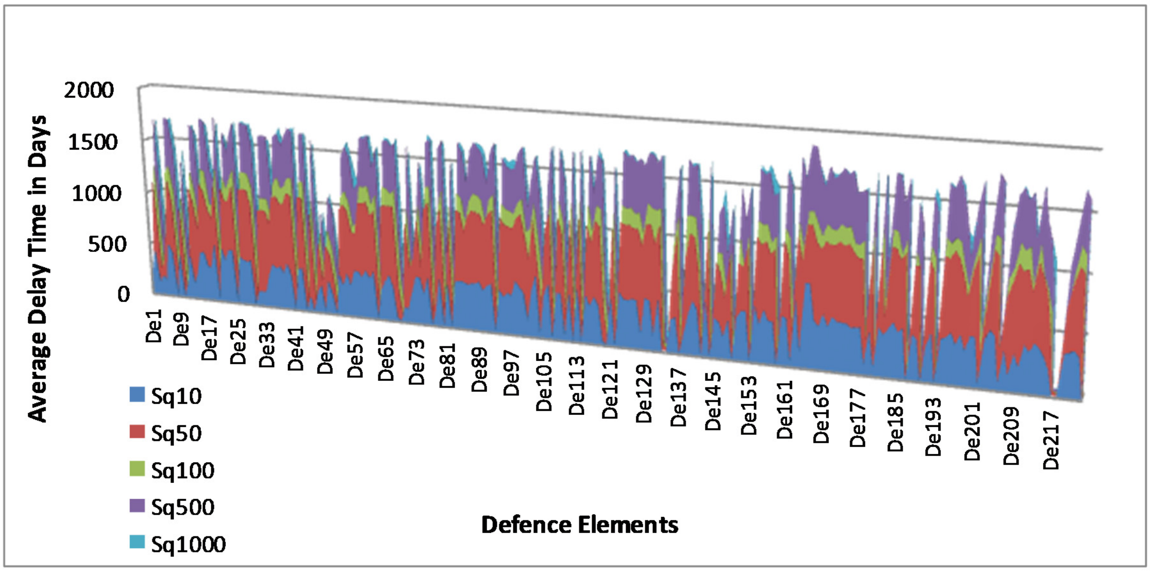


Figure 4. Defence Element Responsiveness as a Function of the Number of Concurrent Events

In Figure 4, we can see that deployment of Defence Elements becomes increasingly delayed (on average) with more concurrent events (Sq10 to Sq1000). It is clear that higher demand results in more stress on some Defence Elements although there are others that are not affected at all such as airports, bases or infrastructure (e.g. De217). Since such Defence Elements are reusable and immobile, their throughput is effectively unconstrained in our model as measuring individual Defence Element throughput is outside our scope.

6. CONCLUSIONS

We have applied a hybrid simulation model of defence preparedness for the purpose of analysing force structure options from a preparedness perspective in support of the defence episodic review process. Working with an unclassified data set, we have confirmed we can analyse a force structure conducting concurrent operations and identify the over and under stressed Defence Elements. The results presented verify our modelling approach and lay the foundation for analysis of official planning vignettes.

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