The Analysis of Network Centric Maritime Interdiction Operations (MIO) Using Queueing Theory.

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Abstract

In 2001 the Maritime Systems Group of The Technical Cooperation Program (TTCP) set-up an Action Group (AG-1) to examine the "exponential" increases in warfighting capability claimed for Network-Centric Maritime Warfare (NCMW). Analysis of NCMW is a two-stage process of finding analysis processes for estimating the NCMW effects on the scenario parameters and then applying appropriate warfare models to relate NCMW-sensitive scenario parameters to force effectiveness. This paper will report on the results of a modeling workshop held by AG-1 in November 2002. The workshop's focus was to investigate the usefulness of applying a queueing model to Maritime Interdiction Operations (MIO) within the context of the NCMW concept of tactical collaborative planning.

Both analytical and simulation-based queueing models were examined, and the theoretical model was applied parametrically to two MIO scenarios. Using the steady-state probability of target vessel interdiction (i.e., service) as the primary measure of effectiveness, the workshop was able to demonstrate the usefulness of queueing to relate NCMW application measures to force effectiveness. In addition, the queueing models provided valuable insight into the aspects of the MIO task where NCMW concepts might be applied. Thus, queueing is directly applicable to the second stage of analysis for operations that can be viewed as a demand for service, and provides direction in the process of refining NCMW concepts into testable applications. The parametric results from the workshop provide general bounds on expected improvements in effectiveness; however, specific results will depend upon the particular NCMW applications and how they are used.

Introduction

There have been a large number of studies written about the perceived benefits of network-centric maritime warfare, but few studies have taken an analytical view, and produced quantitative results [1]. Given the variety of opinion in the literature and the military interest in Network Centric concepts, The Technical Cooperation Program (TTCP) [1]Maritime Systems Group (MAR) set up an Action Group (AG-1) on coalition network-centric maritime warfare analysis to redress the lack of quantitative analysis, and assist in program development. AG-1 has established two projects to study NCMW in breadth and depth, and is to complete its work by September 2004.

The first AG-1 study is an assessment of the broad issues and concepts in NCMW. A number of broad issues papers, including a "first principles" paper, are being written to help define what NCMW means to coalition warfare, and to survey a broad range of applicable operational research tools that may be useful in the analysis of NCMW [2]. The study will also conduct an analytical study of the NCMW effects on operational

[1] TTCP is a collaborative exchange program in non-nuclear defence science and technology between the governments of Australia, Canada, New Zealand, United Kingdom and United States of America.

issues such as Intelligence, Surveillance and Reconnaissance (ISR) and force level collaborative planning using MIO operations for context.

The second AG-1 study is an assessment of tactical level NCMW issues, with an in-depth analysis of NCMW in a variety of scenarios. There are currently five hypotheses, each situated within a tactical context (TACSIT). Each hypothesis will be "tested" to quantify the utility of coalition force network-centric capability. This paper on maritime interdiction operations (MIO) tackles the first of the five hypotheses and presents results from the first AG-1 modelling workshop held in Auckland, NZ, in November 2002.

Using this combination of higher-level investigations in concert with more detailed studies of specific network centric applications AG-1 hopes to be able to fulfill its mandate to support the national programs of the five participating countries, and provide guidance to the MAR group principals as the overall MAR scientific program moves forward.

NCMW Analysis Process

The key problem in modelling the war-fighting effectiveness of applications (network centric or not) lies in linking the local effects of the application to engagement/scenario measures of effectiveness. It is rare, due to the complex nature of warfare, that an application has such an effect that it dominates a scenario by itself. Instead a (at least) two-stage approach is required:

1. Determine the local effects of the application on "engagement" parameters by calculating Measures of Performance (MOP) for the application;
2. Use an appropriate engagement model to link the MOP inputs to engagement/scenario Measures of Effectiveness (MOE).

The first stage requires a detailed description of the application and the underlying processes involved in the warfare scenario. The second stage can, at an aggregate level, often be done using fairly simple simulations or analytical tools, although in more detailed analyses complex simulations are often used.

Conducting an analysis in the forward direction (stage one followed by stage two) requires defining the application and scenario in some detail, and is the usual method when conducting the analysis of a specific, well-defined concept or piece of equipment. However, when systems are vaguely understood, analysis is often conducted by starting with a parametric evaluation of stage two in order to develop an understanding of the warfare operation. The understanding thus developed can then be used to suggest and develop specific concepts or equipment.

This latter case is the situation the AG found itself in. Since NCMW is characterized by the human use of technology, and the technology itself is in a state of constant flux it is difficult to tie down a single NCMW application/concept in enough detail for testing and analysis. Further, the current data available from operations had not been collected with analysis in mind and lacks the coherence and consistency required to be of more than general use.

The first few meetings of the AG were totally devoted to determining the scope of the problem and then limiting that scope to an achievable set of goals for each study.

MAR AG-1 adopted the following statement from the U.S. Naval Studies Board [3] as its working definition of network-centric maritime warfare (NCMW):

> …military operations that exploit state-of-the-art information and networking technology to integrate widely dispersed human decision makers, situational and targeting sensors, and forces and weapons into a highly adaptive, comprehensive system to achieve unprecedented mission effectiveness.

Work in the higher-level study has led the AG to conjecture that it is a change in the focus of the use of technology, more than the change in technology itself, that is the revolutionary part of NCMW. That this change would be unlikely without the profound changes in technology currently occurring should not be lost, however, it is the change in human-based processes and procedures that is required to obtain the revolutionary changes in capabilities that have been forecast.

This presents a major problem to the modeller since models of human behaviour and decision-making are notoriously difficult to develop in all but the most general or most specific of circumstances. That is either where a large numbers of decisions can be aggregated together to obtain steady-state system behaviour, or where the situation is so specific and limited that the details can be modelled.

From AG-1's initial investigations a number of hypotheses about tactical NCMW applications were developed to address a variety of tactical level war-fighting scenarios. The first of these to be tackled pertains to the Maritime Interdiction Operations (MIO) tasks that have been a common feature of most recent coalition operations. The hypothesis is:

> *In coalition force MIO operations, network-enabled collaborative planning/re-planning increases the probability of intercepting a contraband vessel.*

The associated null hypothesis is that network-enabled collaborative planning/re-planning does not increase the probability of intercepting contraband vessels.

Maritime Interdiction Operations (MIO)

A maritime interdiction operation (MIO) is a naval task, usually conducted with maritime air support that may involve: the surveillance and interception of commercial or private vessels; visiting, boarding and searching suspicious vessels; detaining or diverting non-compliant vessels to a designated area or port; and seizing a vessel (and cargo, crew and contraband) when the master of the vessel is found in violation of the sanctioning authority. This naval task is referred to by some countries as maritime *interception* operations, and is generally conducted under the legal authority of the United Nations, or some other sanctioning body. Strict rules of engagement apply, and in general, non-deadly force is considered before using deadly force. [4]

MIO operations are essentially the blockade functions traditionally employed by naval forces. They can be employed under a declaration of war, as part of a set of sanctions against a particular nation or organization, or indeed as part of the defensive operations for a particular nation. Examples of these operations in the recent past are: the trade embargo operations against Iraq, searches for terrorists in the Persian Gulf[2], anti-immigrant operations in Australia and Canada, and general anti-smuggling operations.

MIO operations can form a large part of both peacetime and wartime naval operations; particularly for mid-size and smaller combatants. Since MIO-type operations are so broadly applicable, they provide a good initial area for the study of NCMW effects. In addition, they are more critically dependent on information and command and control (C^2) than on specific weapon systems, which simplifies the problem space and analysis.

In essence, MIO operations consist of a set of naval forces trying to find and apprehend (possibly deter) targets of interest (TOI) carrying contraband (goods or people). The TOI may be mixed in with legitimate vessels. Typically, the TOI must be identified and apprehended in some specific area so that it can't pass through that zone and evade the blockade. The required criteria for apprehending vessels can vary, but typically determining the criteria requires close examination by the interdicting force. These identification processes may require several levels of examination by different units, and may be applied to all vessels or a just a sample of them. The task of the TOI is escape the interdicting force through manoeuvre or deceit.

In an MIO, the vessels of interest (or targets) may wait in a queue, and are later served (or queried, and perhaps inspected and boarded) by warships on patrol. This service also takes time. No two operations are identical but they are characterized by a sequence of actions starting with a query into the vessel's intent, often followed by a search for contraband by a boarding party, and ends in a decision to either apprehend the vessel or allow it to continue.

Application (Collaborative Planning and re-Planning)

Collaborative planning and re-planning assumes that, under a general Commander's Intent, dispersed individual commanders can make use of networked communications to develop plans in collaboration as if they were a co-located command. Thus, a MIO force would develop and coordinate their initial plans over the network. The commanders can then make joint decisions on changes to an existing plan as circumstances change. The difference between planning and re planning is really only one of timing since few plans exist in a vacuum. Planning however is often thought of as being an operational level exercise/task done by dedicated command staff, while re-planning in this context is a tactical task. In both cases the NCMW application involves doing the normal command staff jobs (for tactical or real time planning) in a distributed fashion. So that while units are dispersed and in the midst of operations their views and inputs can be obtained in planning or adjusting the operations to adapt to unforeseen circumstances. In a coalition operation there is a further benefit that all nations and their particular requirements can be included in the plans. Coalition operations are fraught with possibilities for misunderstanding and require significant effort to be put to maintaining relations between the partners. Collaborative planning may provide an additional channel for these efforts - hence the reason for the AG-1 hypothesis.

[2] These operations are often called leadership interdiction operations (LIO).

Technology Required

In these concepts it is important to have the communications links to allow the coalition partners to exchange ideas and come to agreement on a course of action. Depending on the command structure this may lead directly to implementing the new plan or it may lead to a proposal to the operational commander. In addition, the overall commander may be directly involved (actively or monitoring) in the process. Twenty-four-hour-a-day, seven-days-a-week (24&7) real-time communications with sufficient bandwidth to pass relevant information (plans, intelligence, maps etc.) are required. All participants will require the systems to display and analyse the information. As well, common, well understood collaborative software is necessary to enable the capture of ideas, issues and decisions, and to enable debate.

The expected outputs and results of the use of collaborative planning and re-planning are:

1. Improved synchrony between units since unit commanders understand their partners' parts in the plan and their concerns about the plan;
2. Increased flexibility in operations because the overall force is able to respond in an adaptive manner to new circumstances;
3. Improved use and understanding of sensor and intelligence data;
4. Better matching of force to threat since units can redeploy to match a threat;
5. Deconfliction of the battle space. Since everyone participates in the (re-)planning there will be fewer problems of water space or airspace management;
6. Decreased HQ workload since virtual command teams can be formed outside of the operational level command;
7. Increased ownership of plans by all units or nations involved since everyone has been involved in the plan development; and,
8. Increased speed and quality of command.

Queueing Model

Many warfare areas can be characterized by a demand for service, and as such can be analysed using queueing models. A queueing model consists of a set of things arriving at a system and seeking service (or to avoid service), a number of servers seeking to provide (impose) service, and a set of behaviour guidelines for arrivals and servers. Figure 1 shows a general queueing system. Arrivals show up at the queue (operating area) according to a probability distribution and either enter or balk (retreat). Those that enter will sit in the queue until either they are serviced, or they renege (get tired and leave, or evade the servers). Both reneging and service are also governed by probability distributions. While it is possible that an arrival will renege while in service this will not be modelled in the work below. Under a common assumption of exponential probability distributions; arrival, service and renege times are governed by mean rates (λ, μ, and α respectively) which provide three of the main model inputs, the other two being queue size and the number of servers.

The work conducted by AG-1 and reported in this paper used an analytical queueing model based upon exponential arrival, service and renege distributions[5], which was implemented in an Excel spreadsheet. In the situations used in this work the exponential distributions were found to be reasonable and gave comparable results to those a simulation-based queueing model [6] using a variety of other distributions. Since the spreadsheet model was much faster and easier to run than the simulation this facilitated the conduct of the workshop.

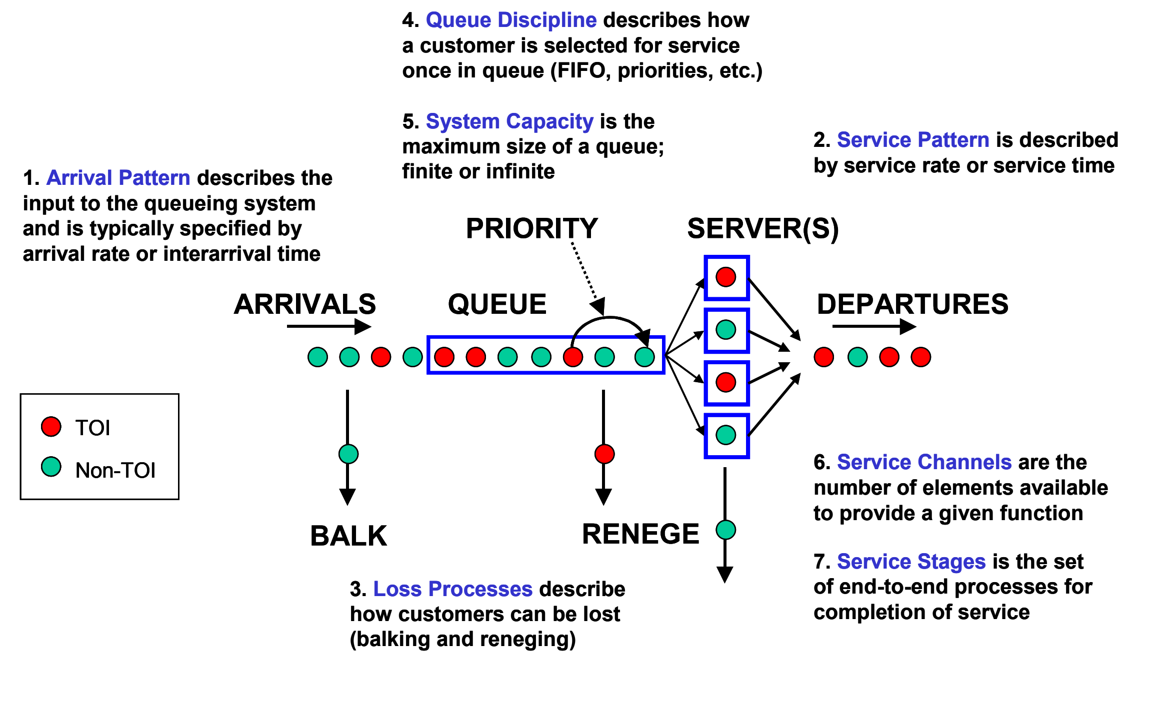

Figure 1: Queueing Model Elements

Queuing Theory Results for Collaborative Planning

In this section two MIO blockade scenarios are simulated using queueing models and the results are analysed to develop an understanding of where coalition collaborative planning/re-planning might assist the war-fighter.

Countering Breakouts in a Blockade

One of the expected effects of Network Centric Maritime Warfare is improved intelligence about opposing force plans. It is clear that if the arrival rate increases, then the time-to-service must decrease and/or the number of interceptors must increase to maintain a given Probability of Interdiction. However, it will often be unlikely that extra interceptors will be available in the time frame required. It is to be expected that an opposing force will pick a time when the interception forces are weakest to attempt to break a blockade with a surge in arrivals or to run a high value cargo through.

It is also unlikely that an opposing force will be able to increase the arrival rate equally across the entire barrier or over a significant time period. However, including physical or geometrical constructs in queueing models must be done indirectly; for example the estimation of the mean interception time component of the mean service rate. As a baseline assumption targets arrive completely at random along the MIO barrier and interceptors are essentially uniformly distributed along the barrier as well. However, if through improved Intelligence, Surveillance and Reconnaissance (ISR) the intercepting forces can predetermine that the targets of interest will all be arriving in one part of the barrier it may be possible using collaborative planning to dynamically re-deploy the interceptors to meet the increased arrivals.

To examine this situation AG-1 looked at three operational cases:

1. Baseline Case: N interceptors are assigned to N independent operational sectors such that the expected target densities are evenly distributed amongst them (N individual queues of 1 server and λ/N arrival rate);
2. Blockade Breakout Case: Interceptors distributed as in the Baseline case, but the full expected target arrival rate occurs in a single sector of the barrier (a single queue of 1 server and λ arrival rate); and,
3. NCMW Improved Case: The expected target arrival rate occurs in one sector as in the Blockade Breakout Case, but is now faced by all N interceptors (a single queue of N servers and λ arrival rate).

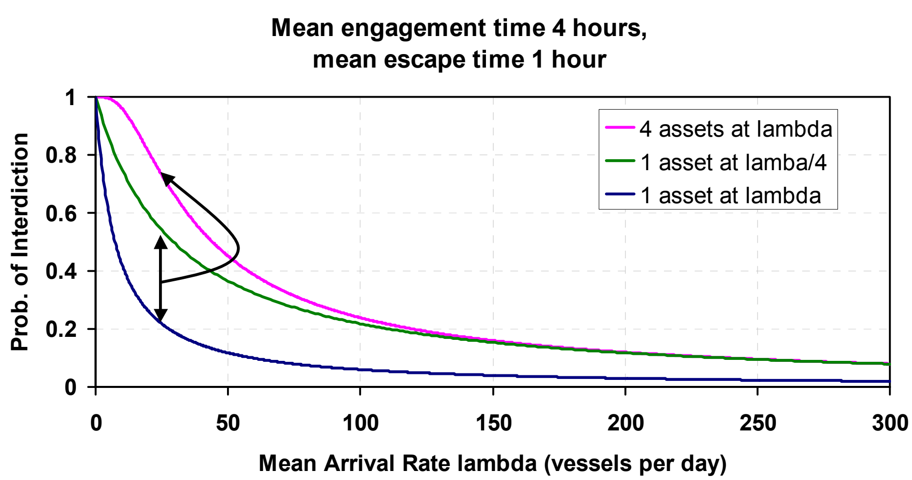

Figure 2: Effect of Collaborative Planning in matching servers to expected arrivals. The green line is representative of four independent sectors each with a mean arrival rate of λ/4. The blue line is representative of a single sector facing a mean arrival rate of λ, and the magenta line is representative of a single sector facing a mean arrival rate of λ but with four servers available.

The cases were modelled using N=4 interceptors. In Figure 2 the curves resulting from a queueing model of the three situations are shown for varying levels of target arrival rates. The middle (green) curve shows the Probability of Interdiction for the single interceptor facing its share of the expected arrival rate and operating independently (Baseline Case). The bottom (blue) curve shows the performance of the single interceptor when four times the targets show up (Blockade Breakout Case), while the top (magenta) curve shows the effect of having all four networked interceptors available to handle the increased arrival rate (NCMW Improved Case). To follow through the scenario for an overall arrival rate 25 targets per day then the individual interceptors in the Baseline case would have a probability of interdiction of about 52% (green line). However, if the opposing force were to try to overwhelm the blockade by sending all targets against a single sector (Blockade Breakout Case) the probability of interdiction drops to about 22% (blue line). Moving to a Network Centric force with advanced ISR resources and collaborative planning, the force on recognizing that all of the targets are being concentrated in a single sector re-deploys to bring all four interceptors into play (NCMW Improved Case), moving the probability of interdiction up to 72% (magenta). Thus, if Network Centric systems can provide the ISR resources to give the commanders enough confidence to leave the other three sectors uncovered, the force could achieve a 50% increase in capability through the collaborative re-planning of the force response. Indeed, there is a 20% improvement simply by moving from independent sectors to some dependence in the force (moving from the green to magenta lines). Note that as the force capability becomes saturated the difference between independent and assisted sector defences become negligible (magenta and green lines converge at high arrival rates).

For a force used to operating together and under well-understood chains of command and operating concepts, current radio systems may be adequate for the collaborative planning. It is also recognized that human intelligence will often be of more importance than sensor information in blockades. However, in coalition operations it is often true that forces are not used to operating with each other, and the command stream may not be unified but have multiple national requirements and rules-of-engagement that must be taken into account. To obtain the types of response times that may be required to re-deploy to meet a surge of arrivals, demands a cohesive and trusted planning process. Traditionally, face-to-face meetings and explicit planning have been required to develop such a process. The NCMW conjecture is that collaborative planning and other network based command interaction tools will alleviate some of these problems. The above analysis does not say that that collaborative planning/re-planning will accomplish this, but it does point to the types of general improvements in war-fighting effectiveness that may be achievable if the human usage of the tools can improve the command response times and optimise force disposition.

Analysis of Holding Pen MIO Operations

When the renege or escape time is too short for the required full service time or the arrival rate becomes too high, a variant of blockade operations that is often implemented (c.f. Iraqi oil embargo operations) is the use of a holding pen operation. In this type of operation, all or almost all vessels entering the operating area are queried and those requiring full service/search are diverted to a holding area and serviced there. Figure 3 gives a schematic of the situation.

These operations can be viewed as a linked set of two queues with differing characteristics. The initial barrier, or “query”, queue is likely to have

1. a low mean renege time, corresponding to the requirement to catch vessels quickly;

2. a low mean query time to compensate for the low renege time and to maintain a high probability of interdiction;
3. a higher number of servers in order to handle the spatial areas or surges in arrival rate; and,
4. no balking, since a vessel that does not enter the area fails in its mission.

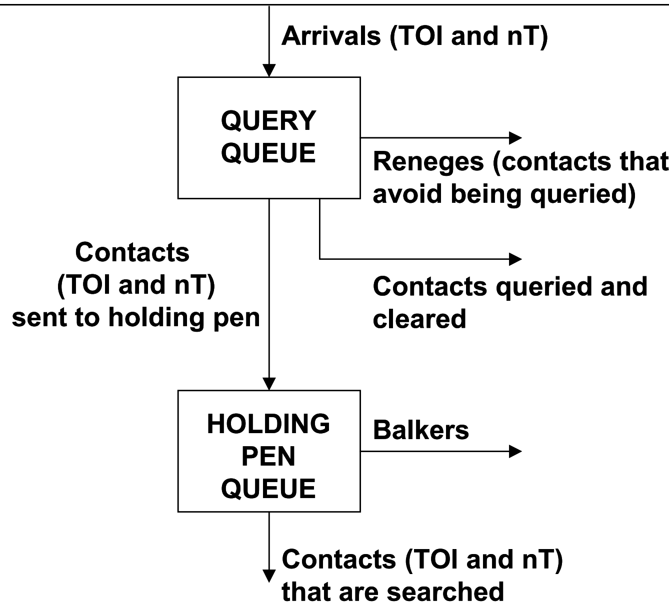

Figure 3: Holding Pen MIO operations flow chart. TOI are targets of interest and nT are non-targets.

The holding pen queue will have:

1. a large mean renege time since the holding pen is guarded;
2. an arrival rate that is dependent upon the serviced departure rate of the query queue;
3. a longer mean service rate to account for the time required for detailed searches;
4. possibly a smaller set of servers; and,
5. possibly a fixed pen size and thus balking (escapees) once the pen is full.

Figure 4 shows overall results from linking two queues as described. The probability of interdiction for the entire system versus mean arrival rate is shown for four cases: a single server with a four hour mean service time; two servers with two and four hour mean service times; and four servers with a four hour mean service time. All four cases use a holding pen size of ten vessels. Essentially, each doubling of servers or halving of mean service time provides a rough doubling in probability of interdiction for a given overall arrival rate. The loss rate for the system includes reneging/escaping from the query queue and balking from the holding pen because it is full. Varying the maximum queue size had a negligible effect on results.

The lack of effect from changing the maximum holding pen size is at first glance counter intuitive since it might be expected that increasing the holding pen size would reduce the number of vessels balking from the holding pen. This is indeed true when the holding pen is initially established, however, so long as the overall service rate is less than the arrival rate the holding pen queue, no matter what its size, will fill before the steady-state is achieved. Thus, once the steady-state is achieved all arrivals over and above the number that can be serviced and released from the queue, in each time period, will balk. Since, the number not balking is independent of the queue size, steady-state performance is also independent of queue size. This is the same phenomena that causes the results in Figure 4 to drop off significantly as the arrival rate reaches and exceeds the overall service rate of the holding pen queue.

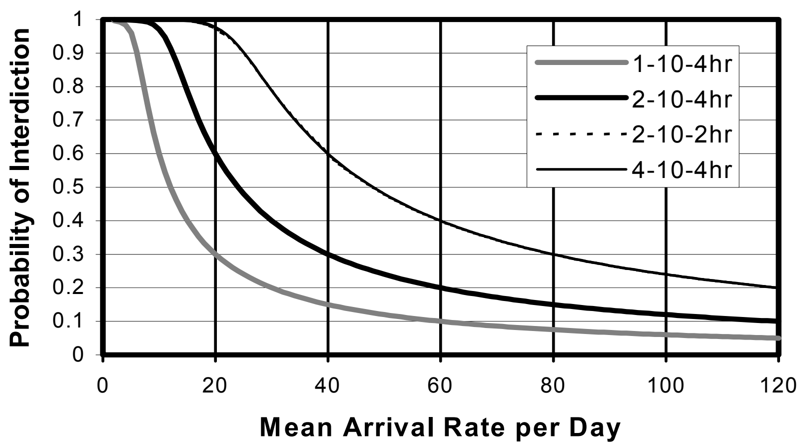

Figure 4: Holding Pen MIO operations steady state probability of interdiction behaviour using 1,2, and 4 servers with a queue size of 10 and 2 or 4 hour mean service times versus mean arrival rate in vessels of interest (TOI) per day. The 2-10-2hr and 4-10-4hr lines are the same to the second significant digit.

The response to such a situation is to either ensure that the overall service rate in the holding pen can handle the arrival rate, or to periodically increase the service rate in order to clean out the pen. In the latter case the size of the queue helps to determine how often the backlog in the pen will need to be cleaned out.

This then points to a planning dynamic in this type of operation. The planning team will need to allocate resources between the barrier and the holding pen (plus escorts between the two). In our previous breakout scenario we argued that collaborative planning would allow the efficient reallocation of coalition effort along the barrier. In this scenario, we make a similar argument, but towards the periodic movement of server resources between the line and the holding pen operations. Even in a homogeneous force the movement of forces between the two areas will require a fair amount of planning in order to schedule refuelling, rest periods etc. Unless overwhelming numbers of forces are available it is to be expected that planners will wish to minimize the numbers of servers in use, thus, allowing for response to breakout operations will require the ability to move servers quickly from the holding pen operations onto the line. Fortunately, it is unlikely that the opposing force will be able to maintain the surge arrival rates, which would allow a build-up in the holding pen to be cleared.

Summary

Queueing provides a good model for examining a class of warfare engagements that are expected to benefit from Network Centric Maritime Warfare (NCMW) concepts and applications. That is, those characterized by a 'demand' for (or avoidance of) service. This fills one of the necessary stages in a quantitative analysis of NCMW concepts, that of linking application measures of performance (MOP) to force measures of effectiveness (MOE). Unfortunately, the hard part of the analysis is refining an NCMW concept down to a testable application or capability, since the actual revolutionary benefits are believed to come from changes in the human usage of technology.

However, the examination of engagement level models and the variation of MOE with the parametric study of input MOPs is an important part of the process of refining NCMW concepts to the point where they can be tested.

Two applications of the NCMW concept of network-based collaborative planning and re-planning were analysed using a queueing model to highlight the capabilities and shortfalls of the methodology. For aggregate steady-state systems queueing provides a rich source of insight. However, the analyst needs to keep in mind that in reality service time and service accuracy often are not stationary processes and interesting phenomena will occur outside of steady-state situations.

From this study of coalition MIO operations there appears to be general evidence to support the continued development of collaborative planning and re-planning applications. To obtain definitive evidence was beyond the scope of the AG-1 workshop and will require the acquisition of baseline capability data, and experimentation with specific applications.

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