Simulation Modeling of Maritime Piracy using Discrete Event and Agent-Based Approaches

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Abstract: In the last decade, maritime piracy has affected the global economy that forced the countries to react. Most of the reaction is regarding force deployment in the affected regions. In this study, we present a simulation based analysis tool that aims at understanding the relationship between naval forces deployment and preventing piracy. We consider three stakeholders' views; pirates, maritime transportation, and naval forces. We initially created a classical Discrete Event Simulation (DES) model and adopted event scheduling approach. However, later, we discovered that since the behaviours of entities, interaction between entities, and the autonomy properties of entities are significant, Agent Based Simulation (ABS) concepts are appropriate for modeling. Finally, we ended up with a hybrid DES and ABS model. Our conceptual model is created using event graphs and the model is implemented using SharpSim DES library. Additionally, we coupled an open source Geographic Information System (GIS), GreatMap, with SharpSim.

1 INTRODUCTION

Continuing impact of piracy and armed robbery at sea remains a significant concern to the international community, nations, non-governmental and commercial organizations. Over 90 percent of the world's trade is carried via maritime transportation (International Maritime Organization, 2011) and as a consequence, anything that restrains or imperils the free transit of vessels in the maritime domain can have serious social, economic and security implications. In fact, the major concern is economics related since maritime piracy is estimated to be costing to the international economy between $7 to $12 billion per year (One Earth Future Foundation 2010). The cost incurred is related to ransoms, insurance premiums, rerouting ships, protection forces, security equipments, piracy deterrence organizations, and effects to the regional economies.

Although maritime security has been a major concern internationally, interestingly, Operational Research/Management Science (OR/MS) community had very little involvement at this problem domain. Jakob et al. (2011a and 2011b) is an exception since they applied Agent Based Modelling and Simulation (ABMS) concepts into maritime security and a simulation tool, AgentC, has been developed. Although OR/MS toolbox includes many other methods and tools that can be applied to help create solutions, the distinction of this problem domain is that maritime piracy is a matter of "behaviour". According to the IMB (International Maritime Bureau), piracy is "An act of boarding or attempting to board any ship with the apparent intent to commit theft or any other crime and with the apparent intent or capability to use force in the furtherance of that act". We believe that this definition suggests that an OR/MS modeller must focus on finding ways of modelling behaviours of pirates, as well as the protection against piracy.

The main motivation of this study is to exploit modelling and simulation to support decision making for maritime security issues and the efforts to protect maritime transportation. We evaluated that an ABS model would depict the behavioural complexities in this problem domain and, as a tool, would also help decision makers understand the relationship between parties involved. In the next section, we review ABS briefly and then present our methodology for this particular study. Rest of the paper is dedicated to the details of our modelling work. First, we present Maritime Security Operations Library (MSOLib), secondly we give some information about the simulation model we

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developed. Thirdly, geographical information system part of our study is presented. We additionally give experimental results to draw some conclusions.

2 BACKGROUND INFORMATION

2.1 Agent Based Simulation

Agent-based modelling and simulation (ABMS) is a simulation approach that models the overall behaviour of a system through use of autonomous system components (called agents) that communicate with each other. ABMS continues to be a rising value of simulation domain for the reason that the main advantage of ABMS is its potential to exhibit the system combined behaviour while just modelling individual agent behaviour.

Siebers et.al (2010) asserts that ABMS enables people to model their real-world systems in ways that either not possible or not readily adapted using traditional modeling techniques. Macal and North (2010) is a classical ABMS tutorial and they suggest that an ABS model have three elements: agents, environment, relation between agents and method of interaction. An agent independently lives in an environment, interacts with its environment as well as with other agents according to its behaviors and experiences in accordance with local information.

Bonabeau (2002) puts forward that agent-based modeling has seen a number of applications, especially in real world business. ABMS applications are not only in business, but also they are widely being applied to spanning human social, physical, healthcare and biological systems. When we update the review, we see that in the last decade the number of papers increased, as well as the domains applied, such as marketing (Siebers et al., 2007), (Filatova et al., 2009), (North et al., 2010), agriculture (Bert et al., 2010), air traffic control (Conway, 2006), biology and health (Emonet et al., 2005), (Davilia and An, 2010), (Kurahashi and An, 2010), (Tang et al., 2011), and military (Moffat et al., 2006), (Hill et al., 2006).

2.2 The Framework of this Study

In our study, we coupled three separate systems to create a tool for evaluating maritime security operations, as shown in Figure 1. The first part is a class library, Maritime Security Operations Library (MSOLib), to maintain the data structures and provide a backbone for the study. The second part is the simulation model. We used SharpSim (Ceylan and Gunal, 2011) DES engine to create an ABS model. To do this, we built Event Graphs for modeling behaviors of every class of simulated units, such as pirates, fishing boats, cargo ships, naval and air units. Finally, to display information and animate the entities (agents) on a map, we created an interface by using GMap.Net (GreatMap, 2011) GIS package.

3 MARITIME SECURITY OPERATIONS LIBRARY

Maritime Security Operations Library (MSOLib) is a dynamic link library which maintains basic maritime contact objects, motion types, detection tools and navigation tools required to simulate a maritime security operation. It is created to work with a simulation library and to maintain objects and data structures. MSOLib hosts;

- Contact,
- Motion,
- Area,
- Sensor,
- Navigation classes.

We implement MSOLib by using C# and it provides full support for object-oriented programming. It works harmoniously with SharpSim and GMap.Net.

Contact class in MSOLib inherits from SharpSim Entity class. A contact instance is an agent in the simulation and its behavior is determined by event graphs as discussed in the next section. There are three main Contact types: Surface Contact, Air Contact and SubSurface Contact.

Motion class is the base class for all motion related activities. There are four motion types and all inherits from basic linear motion. We used Dead Reckoning (DR), Latitude Sailing and Longitude Sailing methods for the linear motion of any maritime vessel at sea. DR is the process of estimating present position by projecting course and speed from a known past position (Bowditch 2002). It is also used to predict a future position by projecting course and speed from a known present position. The DR position is only an approximate position because it does not allow for the effect of leeway, current, helmsman error or gyro error. We neglected these effects and errors. Latitude and longitude sailing methods also use DR sailing when a maritime vessel sail on respectively on latitude and longitude.

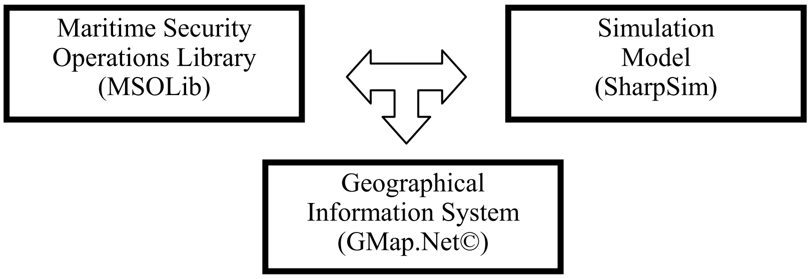

Figure 1: Main component of the analysis tool.

Traverse motion is the motion of the ship between two positions. It moves back and forth between these two positions at specified times. When the contact hits the waypoint, it alters its route to opposite toward to the other waypoint. In random motion, the Contact creates random waypoints in a directed area and when hits the waypoint, it alters its course towards to the next waypoint until it reaches the end point. Path motion works like Random Motion however the waypoints are predetermined by the user.

Area class is required to maintain the agents in an area. It is essentially the environment in the ABS model. Each operation region composed of several number of areas. Each area has its own color, identifier, name, list of points on an operation map and at command and control headquarter. Geometrically, area is a polygon that is declared and specified by naval forces.

Sensor class indicates detector component of the contact. Sensor behaves like a radar system and use IsInsideTheRange method to sweep the environment in sensor range to seek and detect the target. The target's information is provided to the seeker. For example, if a pirate agent attacks a cargo ship, it tries to make a decision according to their freeboard and physical condition by using this sensor. In the sensor class, we used the basic cookie-cutter sensor concept suggested by Buss and Sanchez (2005). This concept assumes that when an entity enters the range of the sensor, a detection occurs.

Navigation classes include necessary utilities for navigational calculations.

4 SharpSim SIMULATION MODEL

SharpSim is a general purposed DES library written in C# to implement models developed with Event Scheduling (ES) approach (Ceylan and Gunal 2011). SharpSim is an open-source code library (http://sharpsim.codeplex.com) and was used in other domains before (Ceylan, Gunal, and Bruzzone 2012).

Since in this study we aimed at building an ABS model, we created Event Graphs (EG) to reflect the behaviors of agents. Once EGs are built, it is easy to convert them to a SharpSim model. Using EGs approach reveals the thin line between DES and ABS, or the power of EGs as a conceptual modeling method.

Our conceptual model (Event Graph) has more than 50 events and it is not possible to demonstrate the whole, an excerpt is given in Figure 2. This EG is a part of navy patrol ship model and is described in the following section.

At the beginning of the simulation, a Run event is scheduled to the future event list which triggers the Ping, Convoy, Group, and all agent creator events for aircraft, fishing boats, cargo ships, patrol navy ships, and convoy (escort) navy ships. Ping event is the basic animation event which essentially acts as a screen refresher event. It updates all agents' positions on the map. This approach was used by Mack (2000).

4.1 Aircraft Model

An aircraft agent starts its motion and turns on its sensor to detect and identify the contacts in its environment. If the agent identifies a pirate vessel it shares this information with naval forces. Aircrafts use path motion in a patrol area. After patrolling, each aircraft returns its home base. The "sweep and detect (SWandDET)" and "Dispatcher" events are circular events which simulates periodical detection efforts. For example, if the patrolling aircraft detects a pirate vessel, the dispatcher event schedules a new SWandDET event, allow SWandDET event to loop itself, and also schedules update pirate list event. When aircraft finishes patrolling and return its home base, it cancels next SWandDET event by using the

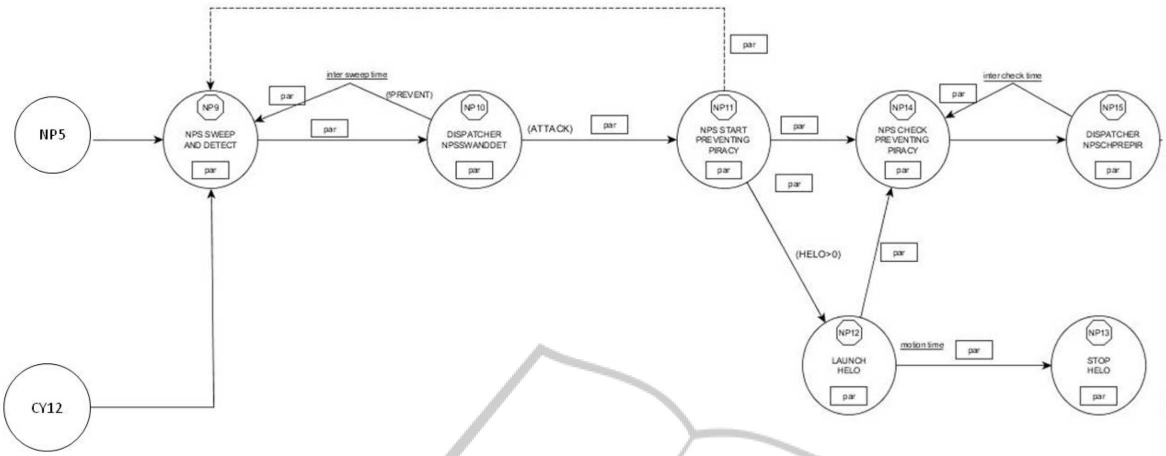

Figure 2: An example of an Event Graph for Navy Patrol Ship.

cancelling edge in the event graph. This edge deletes first SWandDET event from Future Event List (FEL) to turn off its sensor.

4.2 Fishing/Pirate Ship Model

Number of fishing boats and their origin ports are defined by the user. When a fishing ship arrival occurs, next fishing ship arrival event is scheduled after a delay (interarrival time of fishing ship). A fishing boat may also be a pirate ship if certain conditions are met. For example, if a fishing boat's freeboard is low and its speed is high, it is likely that this boat is a pirate boat rather than a fishing boat.

Piracy events start with proceeding to cargo ship transit corridor. When the pirate starts to proceed to transit corridor it turns on its sensor (human vision with binoculars) to detect any vulnerable cargo ship to capture and any naval forces to conceal and protect itself. After each SWandDET event, pirate considers next step of the strategy at the dispatcher event. If pirate ship detects any ship, it tries to classify and identify the contact. After this process, if pirate ship detects any vulnerable ship, it updates its attackable ships list and makes a decision to select a target based on the targets' freeboard, distance, and proximity to any naval forces. It selects the most vulnerable cargo ship (target) by taking into account of these three elements and calculates a risk factor. According to the risk factor it makes a decision to attack. For example, if there is a naval helicopter in the close perimeter, pirate does not decide to attack since helicopter movement agile and nimble, it can easily neutralize the pirate vessel. Pirate starts fishing after decision of "do not attack". On the other hand, it starts to attack the target until pirate captures it for ransom or is neutralized by the naval forces. Unfortunately, if it captures the target, pirate achieved its own mission and successful pirate attack statistics are updated. If it is neutralized by the naval forces, failed pirate attack number and successful naval protection number is incremented. At the time of pirate attacking, a pirate checks its own condition (neutralized or not) and decides to continue the attack or changes its own condition to neutralized and deletes itself from the simulation.

4.3 Cargo Ship Model

Cargo ships' behavior is simple since a cargo ship starts to proceed to the waiting area of the transit corridor. Cargo ship motion on the transit corridor is supervised by the convoy and group scheduled events.

4.4 Navy Ship Model

Naval ships have two tasks; patrolling in a specified area and escorting cargo ships for secure transit in the corridor. We refer Naval Patrol Ship (NPS) in charge of patrolling and Naval Convoy Ship (NCS) for escorting. As in the other agents, NPS and NCS have also sensors to sweep and detect (SWandDET) the environments. After each SWandDET event, NPS considers next action at the dispatcher event. When SWandDET event occurs, NPS does not only sweep and try to detect all over its environment in distance of sensor range but also checks cargo ships' alert state. If it detects any piracy act or any alert state about piracy from cargo ship, it starts to prevent piracy. First, if its helicopter is airborne, it gives orders to the helicopter to quit surveillance and approach to pirate ship. If its helicopter is not airborne, it takes off immediately and proceeds to the pirate ship. Meanwhile the NPS approaches to the target. After the operation, if it fails to prevent piracy, NPS ship reports the result to headquarter and starts to chase the pirate ship. In this case the cargo ship is taken to the captivity region by the pirate. On the other hand, if the operation is successful, NPS neutralizes pirate ship and resumes its patrolling duty and makes a decision for helicopter to land or continue to surveillance. When an NCS arrival occurs, next arrival event is scheduled after a delay (interarrival time of NCS). After each arrival, arriving ship proceeds to waiting area of transit corridor and NCS motion on transit corridor is supervised by convoy scheduled event which will be detailed later

4.5 Convoy and Group Model

There are two transit sailing policy at internationally secured corridors; group transit and convoy transit. The main difference between these two transits is that convoy transit has a naval ship in the group to escort ships, whereas a group transit does not. The aim is to form ships into groups that sail through the secured corridor together. For each group, there is a schedule with entry time and a group speed to bundle ships together. Participation to these groups is neither an obligation nor compulsory. This binding operation is crucial for establishing the security and controlling the transit corridor.

Convoy and group events are time scheduled events. A convoy event has a naval ship which escorts cargo ships to protect them. If the escort navy ship detects any pirate ship or discerns piracy attack alert from cargo ships, it starts to prevent and neutralize pirate ship as mentioned in Navy Ship Model. After the operation, it continues to its transit and escort duty. A group event, however, does not have any naval ship. All cargo ships passes through transit corridor in a bundle that enlarges sensor range of group and causes to alert naval ships before any attack has occurred.

5 GEOGRAPHIC INFORMATION SYSTEM (GIS)

A Geographic Information System (GIS) is a computer-based tool for mapping and analyzing geographic phenomenon on Earth. A GIS is particularly useful for representing input and output of a geospatial environment. As discussed earlier, in our modeling approach we also used a GIS system to display simulating entities on maps. There are three ways of coupling GIS with simulation (Westervelt, 2002): (1) Loose Coupling: A loose connection usually involves the asynchronous operation of functions within each sys-tem. (2) Moderate Coupling: This category encapsulates techniques between loose and tight/close coupling. (3) Tight or Close Coupling: This type of linkage is depicted by simultaneous operation of systems allowing direct intersystem communication during simulation program execution.

There are many GIS packages and tools available and some are already used to couple with simulation. For example OpenMap, an open source Java based GIS package was coupled with Simkit (Mack, 2000). GeoKIT is a commercial Java based GIS package and also was used for a simulation study (Yildirim et al., 2009). We sought to use a .Net compatible GIS package, since our simulation package, SharpSim, is also in .Net. Therefore, we choose GreatMap GIS software (GreatMap, 2011) which is open-source and can use many online map providers, including Google, Yahoo, Bing, OpenStreetMap, ArcGIS, OviMap and CloudMade. On the other hand, it also supports offline use.

In Figure 3, the Graphical User Interface (GUI) of the model is shown. It is the animation of one of the scenarios created for experimentation. Colored icons represent animated agents.

6 EXPERIMENTATION

In our experiments, we investigate the effects of resource allocation and patrolling plans on the success of preventing piracy to make the transit corridor safer for cargo ships.

We made some assumptions that weather conditions are stable and do not influence piracy activity. We also had to neglect possible effects of armed guards at cargo ships.

6.1 Design of Experiments

We altered the values of the inputs; NPS and NPH patrol times, south and west side fishing boat rates, inhibitor coefficients, helicopter ranges, and volume of cargo ship traffic. Number of ships passed through Suez Canal is assumed to be the inputs to the Gulf of Aden, and on average, 17.000 ships pass the canal annually. Number of pirate acts, however, is difficult to adapt into the model. We assumed that some proportion of fishing boats that exist in the region, under some conditions, acts as pirate ships. Examining the historical piracy acts in the Gulf, we observe no trends.

The performance values in the model are general variables for measuring success of naval operations. Model outputs are average successful piracy ratio, average neutralized pirate ratio, average success ratio of pirate ships, average neutralization ratio of NPS, average neutralization ratio of NPH, average neutralization ratio of NCH, utilization of NPS, and utilization of NCS.

Table 1: Factors and Levels of Experimental Design.

Levels/ Factors	Level-1	Level-2	Level-3	Level-4
MPRA	a patrol in 300 minutes	a patrol in 600 minutes	not planned for patrolling	-
NPS and NPH	doubled size NPS w/helicopter support	NPS with helicopter support	only NPS ships	none of NPS and NPH
NCS	five NCS per day	one NCS per day	two or three NCS per day	-

We produced 36 different scenarios (3x4x3=36) (3:MPRA Levels; 4:NPS Levels; 3:NCS Levels) by changing parameters of patrol policy and resource allocation parameters in Table 1. There are normally 3 NPSs, and 5 convoy groups in 24 hours. In table 1, NCS level 1 means that each convoy is escorted by 1 NCS, and in level 2, 1 NCS per day is scheduled. Each scenario is run for 5 times. Outputs generated by the model are average successful piracy ratio, average neutralized pirate ratio, average success ratio of pirate ships, utilization of NPS, and utilization of NCS. The run length is for one simulation year after a warm-up period of one month.

6.2 Results

Since we aim to make some general inferences on the relationship between naval resource levels and success of operations, simulation results are given in a relative manner and should not be interpreted in an absolute manner. In all our experiments, the confidence interval values are small and negligible; therefore the mean values are enough for analysis.

Although comprehensive experimentation results exist (Varol, 2012) we give a limited version in this paper. For example, as the output variable, we have only taken "Average Prevent Piracy" (APP) ratio into account. Scenarios no. 13, 16, 22 and 23 have generated the uppermost values which are respectively; 0.9980, 0.9973, 0.9970, and 0.9966. Additionally, scenarios no. 9, 8, 33, 7, 3, and 6 bring forth the lowermost values which are 0.5695, 0.8220, 0.8493, 0.9075, 0.9225, and 0.9301, respectively. Figures 4, 5, and 6 shows that the uppermost results are gained in NPS factor at "double sized" level at each level of MPRA and NCS factors (plus signs). On the other hand, NPS factor at "no ships" level caused the lowermost results (diamonds). In addition, increasing the number of NCS ships in the region causes to increment in APP ratio. Furthermore, when NCS factor hits the peak, results also reach topmost level.

Keeping both NCS and MPRA factors levels at their own highest points, the simulation creates nearly the same results (all shapes except diamonds at Figure 6) at different levels of factor NPS except "no ships" level (diamonds at Figure 6).

In addition, rectangles and triangles at Figure 4, 5, and 6 show us, either using or not using helicopter to prevent piracy has a little effect on the APP ratio and the difference is not significant. Therefore, having helicopter resource on-board is not necessary if NCS ships carry helicopters.

7 CONCLUSIONS

Maritime piracy has been an issue for over a decade and caused some economical problems in global scale. OR/MS methods and tools can help tackle such issues and in our study we made an attempt to this end. We created a simulation tool for decision makers to understand the relations between pirate behavior and naval force planning.

Our methodology was developed in three stages; firstly we created a class library to create a back-bone for the study. This includes contact, motion, area, sensor, and navigation classes. Secondly, we built an EG to model behaviours conceptually. Later, based on the EGs we converted the conceptual models to DES models. In this way, we treated a DES model as an ABS model. Finally, to animate agents on a map, we coupled the MSOLib, the SharpSim model, and a GIS software.

Experiments presented in this paper are given for demonstrative purposes. The interpretation for the given experiments is that deploying a helicopter either on NPSs or NCSs is fulfilling the tasks for preventing piracy.

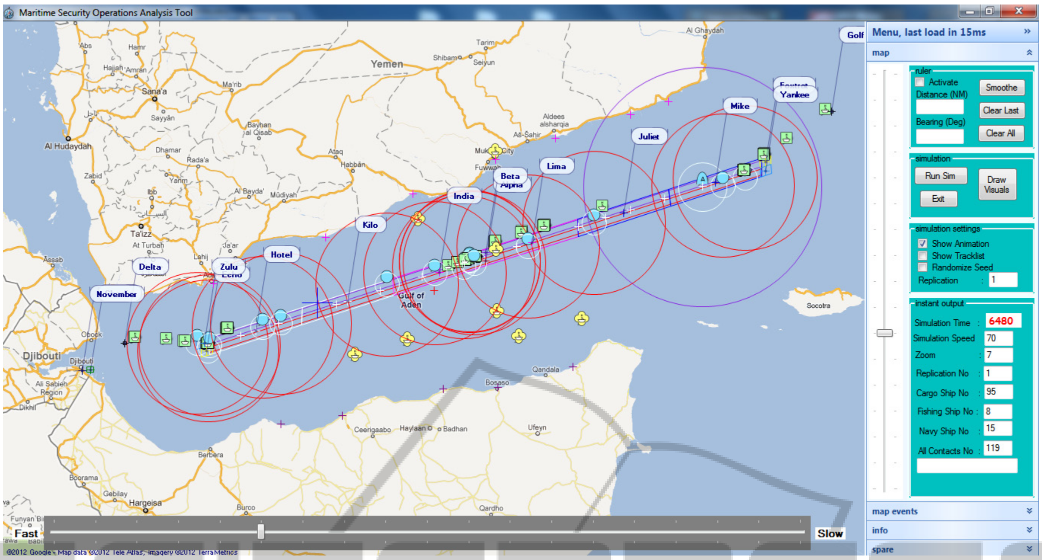

Figure 3: Graphical User Interface of the Model.

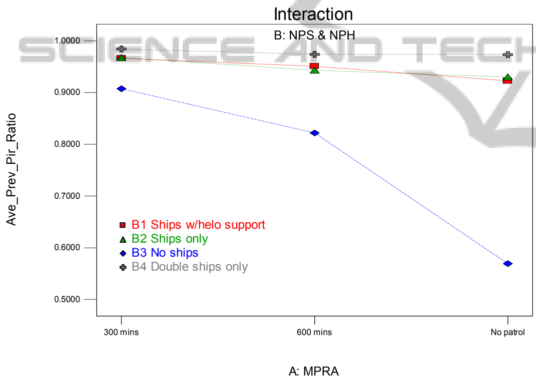

Figure 4: Interaction of Factors for APP Ratio (NCS at level 1).

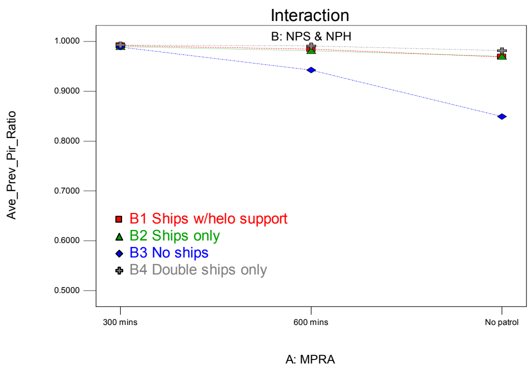

Figure 5: Interaction of Factors for APP Ratio (NCS at level 2 or 3).

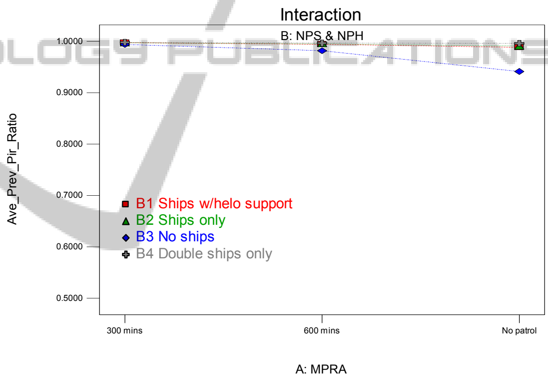

Figure 6: Interaction of Factors for APP Ratio (NCS at level 5).

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