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THESIS

WEAPON-TARGET PAIRING; REVISING AN AIR TASKING ORDER IN REAL-TIME

by

Brian Zacherl

September 2006

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Well-publicized lost opportunities for U.S. and coalition air forces to strike enemy leadership targets in Afghanistan and Iraq demonstrate the importance of Time Sensitive Targeting. How do we "pair" the weapon and weapons delivery platform with their target? The available platforms (aircraft, manned or unmanned) may be on the ground in an alert status, loitering airborne, or on their way to attack other targets. The problem is compounded by the facts that we actually wish to (a) create multiple strike packages simultaneously, (b) recompose existing strike packages that are disrupted by the new plans, (c) minimize such disruptions, (d) satisfy minimum kill probabilities, and (e) avoid the attrition of tasked assets. This thesis develops an automated, optimizing, heuristic decision aid, "RAPT-OR," that rapidly revises a current Air Tasking Order (ATO) to meet the requirements above. RAPT-OR identifies, verified, near-optimal ATO revisions, on a desktop PC, in less than two seconds, for a typical scenario with 40 aircraft, 4 new targets and thousands of potential strike packages. RAPT-OR allows decision makers the ability of adjusting risk acceptance in the formulation of possible courses of action by manipulating friendly attrition importance in formulating a solution.

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WEAPON-TARGET PAIRING; REVISING AN AIR TASKING ORDER IN REAL-TIME

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ABSTRACT

Well-publicized lost opportunities for U.S. and coalition air forces to strike enemy leadership targets in Afghanistan and Iraq demonstrate the importance of Time Sensitive Targeting. How do we "pair" the weapon and weapons delivery platform with their target? The available platforms (aircraft, manned or unmanned) may be on the ground in an alert status, loitering airborne, or on their way to attack other targets. The problem is compounded by the facts that we actually wish to (a) create multiple strike packages simultaneously, (b) recompose existing strike packages that are disrupted by the new plans, (c) minimize such disruptions, (d) satisfy minimum kill probabilities, and (e) avoid the attrition of tasked assets. This thesis develops an automated, optimizing, heuristic decision aid, "RAPT-OR," that rapidly revises a current Air Tasking Order (ATO) to meet the requirements above. Using a set-packing model, RAPT-OR an ATO near optimally, on a desktop PC, in less than two seconds, for a typical scenario with 40 aircraft, four new targets and hundreds of potential strike packages. RAPT-OR allows decision makers the ability of adjusting risk acceptance in the formulation of possible courses of action by manipulating friendly attrition importance in formulating a solution.

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Professionally, as a Marine, I owe a thank you to my second reader, and fellow Marine aviator LtCol. Serg Posadas. LtCol. Posadas saw the value in the research and model found in the following pages and served as a mentor and sounding board when I needed to vent about how things were not going the way that I thought that they should be. Also I wish to thank another warrior; LTC Andy Hernandez USA, who helped out of the goodness of his own heart when he noticed my floundering in the infancy of this thesis. LTC Hernandez helped scope the topic, and helped get me out in the actual field for valuable research.

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took all other advisors out of the immediate area. Professor Wood is responsible for making the following pages readable to someone other than a Marine attack pilot.

Again, thank you, what you have done for me has not gone unnoticed.

EXECUTIVE SUMMARY

When a time-sensitive target (TST) is identified in an active military area of operations, planners must quickly revise current air tasking orders (ATOs) to re-task available air missions and strike this new, high-priority target immediately. This re-tasking must take into account the current coverage of known targets, risks of attrition, probabilities of successful prosecution, and the time window over which the TST is vulnerable. In the current decision cycle for time-sensitive targeting, re-tasking must be accomplished in less than three minutes.

Airpower was recently used to neutralize a significant terrorist threat and enemy in the Iraqi area of operations, Abu Musab al-Zarqawi. In this well-publicized example, we saw ground forces find, fix and track a textbook TST. The offensive operations cell in the Air Operations Center (AOC) at Al Udeid Air Base, Qatar, targeted this TST with two F-16s carrying precision-guided munitions, but they did so without an analytical decision aid. The Zarqawi attack may be viewed as a success for the current TST targeting process, but the same conflict contains examples of failures, too.

Furthermore, a success may only be partial if re-tasking takes strike assets away from other targets, these assets cannot be replaced, and other high-priority targets cannot be hit. Could the AOC have “juggled” its assets more effectively? Clearly, revising an ATO effectively, in the context of TSTs, is a complicated, highly constrained, optimization problem that must be solved very quickly.

This thesis develops an automated, optimizing decision aid, the Rapid Asset Pairing Tool-Operations Research (RAPT-OR), for the purpose of quickly revising an ATO to account for one or more TSTs. It consists of an integer-programming formulation of the ATO revision process, a link to a commercial solver that provides an optimal revision to a given ATO, and a heuristic algorithm that produces near-optimal revisions very quickly. RAPT-OR also has a spreadsheet interface that presents all relevant data in a format that is easy for operators to understand and modify. Results are reported directly in the spreadsheet and highlight the changes to the current ATO, the probability of successful prosecution of each TST, the probability of attrition of each

mission assigned to a TST, and other data to help inform a planner's ultimate decision. RAPT-OR can provide several near-optimal courses of action in seconds, and contains user-controlled parameters to define (a) target priority, (b) the importance of risk aversion, (c) strike-package size limits, and (d) other factors that influence the final revision. The user may adjust these factors, re-solve the model several times, and produce several alternative courses of action in the three-minute re-tasking window.

In a test scenario with two simultaneous TSTs, over 20 ATO missions and 10 incumbent targets, the RAPT-OR heuristic finds a near-optimal solution almost instantly, and, using commercial optimization software, finds the top four re-tasking solutions in a matter of seconds. Each of the resulting plans successfully prosecutes two new TSTs, requires few changes to the current ATO, combines strike platforms with electronic warfare platforms to keep all attrition probabilities extremely low, and keeps all prior targets sufficiently covered.

RAPT-OR is easy to use, and can provide valuable analytical support for revising an ATO in a time-constrained setting. It could even be used to help generate the original ATO. The heuristic algorithm provides near-optimal solutions almost instantly, and is available to any user of Microsoft Excel. (Of course, RAPT-OR should be interfaced with common operating picture (COP) software for best results.) RAPT-OR could also be extended to help coordinate an entire joint fire support environment.

I. INTRODUCTION

A. PURPOSE AND OVERVIEW

When new high-priority targets arise in an active military area of operations, planners must revise current air tasking orders quickly to strike these targets. Frequently these are "Time Sensitive Targets" (TSTs) that present a short time window of vulnerability. A study of Air Operations Centers (AOCs), the organizations that perform this planning, shows a requirement for a decision aid to help revise incumbent plans when such time sensitive targets appear [Jumper 2004]. This thesis develops an automated, optimizing decision aid, the Rapid Asset Pairing Tool-Operations Research (RAPT-OR), for this purpose.

RAPT-OR comprises a set-packing optimization model and model generator, a heuristic solver, an optional exact solver, a database and a graphical user interface (GUI). The model generator strips target assignments from the missions defined by the current Air Tasking Order (ATO), and combines these "targetless missions" in various ways with various targets to form a large set of potential strike packages. (Some of these will be identical to those strike packages implicitly defined in the current ATO.) The model then assigns a "reward" to each strike package that accounts for target value while penalizing for risk of attrition, distance traveled, changes incurred over the current ATO and other factors. The RAPT-OR heuristic solver (or the optional exact solver) then selects a subset of the potential strike packages that tries to (a) strike all pre-existing and new targets, (b) minimize disturbances to the original ATO, (c) satisfy minimum desired kill probabilities, and (d) avoid attrition of the tasked friendly assets.

By solving the optimization model heuristically, rather than with commercial mathematical-programming software, RAPT-OR can be rapidly distributed and reliably operated without the expense of licenses and special training. This is crucial in an expeditionary, military environment. However, we verify that the heuristic works well by comparing heuristically obtained solutions with provably optimal ones.

B. BACKGROUND

1. Problem Statement

The current conflicts in Iraq and Afghanistan are filled with examples of TSTs, i.e., targets of critical importance with fleeting opportunities for striking. One need only look at the well-publicized lost opportunities to strike enemy leadership targets in both countries to see the importance of managing the process of "time-sensitive targeting" (for example, attempts to destroy Osama Bin Laden or Ayman al-Zawahiri [Lambeth 2005]).

At its roots, the problem of managing time-sensitive targeting is one of managing many short decision cycles [Lambeth 2005]. In order to "kill" a TST as it moves across the battle space, the attacking side must form and execute its strike plan quickly. Planners must assign available strike assets to the new target, and if those assets are taken away from existing targets, the planners must reassign the now-uncovered targets to other assets, if at all possible. Furthermore, planners must try to ensure that the reassignments meet kill-probability goals, do not pose undue risks of attrition to the attacking aircraft, and keep plan turbulence to a minimum; by "plan turbulence," we mean wholesale changes to the current plan that would require excessive amounts communication and coordination, and would introduce many chances for mistakes. In an environment that might involve scores of targets and hundreds of aircraft, it is clearly impossible for a time-constrained human planner to revise an ATO optimally or near-optimally to respond to a TST.

But time is highly constrained because the TST may quickly disappear, and because the available pool of assignable aircraft includes (a) some that are, at that moment, flying toward previously assigned targets, (b) some that may be about to launch from the ground or aircraft carrier toward previously assigned targets, and (c) some that are loitering in the air, consuming limited fuel, waiting to be assigned to a target. Clearly, a fast, automated decision aid is needed for this ATO re-planning process.

2. The Air Tasking Order (ATO), Strike Packages, Missions and Targets

A number of the terms associated with air tasking mean different things to different organizations throughout the U.S. military. For the sake of clarity, this thesis applies the following standardized definitions:

- Target: "A target is an area, complex, installation, force, equipment, capability, functions, or behavior identified for possible action to support the commander's objectives, guidance and intent." [JP 1-02]
- TST: "[A target] of such high priority to friendly forces the Joint Force Commander designates it as requiring immediate response because it poses (or soon will pose) danger to friendly forces, or it is a highly lucrative, fleeting target of opportunity." [JP 1-02]
- ATO (Air Tasking Order): The published plan for a specific military theater that encompasses all elements of the air operation: mission scheduling, airspace, air defense, in-flight refueling plan, communication plan, electronic warfare, search and rescue, suppression of enemy air defense, special instructions and rules of engagement.
- Mission: A single assignment of one or more like aircraft in an ATO. Missions dealing with "strike" or attack of surface target are of primary concern to this thesis. As in Weaver [2003], we assume that the need for quick re-planning means that a mission can not be divided into its sub-elements of individual aircraft. All missions are assumed to be associated with a specific target at time of launch. If a mission is launched to loiter, and be tasked airborne, it is given an artificial, place-holder target.
- Strike Package: A combination of missions (of possibly like or unlike aircraft types) that is designed for the destruction of ground targets or the suppression of enemy air defense. Each strike package is associated with a target, or target-threat combination.

- Threat: An enemy surface-to-air missile system or fighter aircraft protecting a target. Threats can be targets. Threats have an associated potential to attrite friendly aircraft.

The ATO is the document that prescribes (and schedules) all missions for manned aircraft, whereas the Integrated Tasking Order (ITO) covers both manned and unmanned aircraft. The methods developed in this thesis apply to both ATOs and ITOs, but, for simplicity, we will refer to the ATO only. Chapter II presents a detailed discussion of the process by which the ATO is created, and the organizations involved in its creation.

Our definition of "target" above correctly implies that planning a strike on a target is normally a deliberate process that can take hours and even days. In contrast, a TST must be handled "on the fly." Planners do account for the fact that TSTs will arise, and will need to be addressed, however.

Planners use certain missions as placeholders for potential TST attacks. For instance, "XCAS" is an ATO identifier specifying on-call, airborne close air support. The XCAS aircraft are fueled and armed, and loiter in a specific area until they are assigned to a target. However, the majority of ATO missions are preplanned against known targets with identified locations, and only a few or no unassigned aircraft may be available when a TST is identified. Thus, revising the ATO to strike a TST while maintaining coverage of previously assigned targets is a complicated, highly constrained optimization problem. This problem must be also solved quickly to provide an answer in the short time window available.

3. Revising an ATO

The factors that guide a good revision to an existing ATO are the same ones that guide the original generation. When determining the "best capable" attack platform(s), the JFC normally incorporates the six factors below in an assessment:

(1) **Effectiveness.** Depending on the desired effects, the appropriate weapons and/or capabilities should be selected. For example, a specific type of attack asset such as a cruise missile may be highly effective in destroying an

unhardened TST, while destruction of hardened TST might require an aircraft-delivered, precision-guided bomb.

(2) **Weapon and/or Capability Responsiveness.** Once a TST is detected, responsiveness is critical to ensure that the attack opportunity is not lost. Responsiveness can be measured as the elapsed time required from receipt of an execution order to weapons impact or effects. (By default then, responsiveness is also concerned with whether or not the chosen weapon system and/or capability can operate given current environmental conditions.)

(3) **Range.** The weapon system that is selected to strike the TST must be able to reach the target without running out of fuel. In the case, of a manned system, it must also be able to return.

(4) **Accuracy.** The weapons system designated for an attack should be able to attack the target accurately. For example, the circular error for unguided weapons might be insufficient to ensure a high probability of kill on a mobile target and thus, precision-guided weapons would be required.

(5) **Threat. A** TST may be located in a heavily defended area. For instance, the existence of a significant air-defense threat may preclude the use of non-stealth aircraft. If air-delivered munitions must be employed against such heavily defended TSTs, assets that can suppress enemy air defense, or electronic attack capabilities, may be required.

(6) **Deconfliction.** This is critical to prevent fratricide, mishaps and unnecessary expenditure of aircraft or other assets. For instance, the flight path of a missile must not conflict, in time and space, with friendly aircraft transiting an area [505th TRS, FUN-234 2002].

RAPT-OR specifically deals with all of the above factors except deconfliction when providing decision-support for an ATO revision.

C. HISTORY OF ATO AUTOMATION

RAPT-OR's history dates back to 2001 when the Space and Naval Warfare Command (SPAWAR) started work on a decision aid to help reassign aircraft when TSTs were discovered during the execution of an ATO. Although SPAWAR was developing its own decision aid, it commissioned Dr. Richard Rosenthal at the Naval Postgraduate School (NPS) to provide a backup. The SPAWAR effort yielded a tool known as the Rapid Asset Pairing Tool (RAPT) [McDonnell et al. 2002]. RAPT uses a genetic algorithm (heuristic), and was received with encouragement. However, it still awaits testing to determine whether or not it delivers tactically useful results. Rosenthal, and Major Davi Castro, Brazilian Air Force, developed an integer-programming model for this purpose [Castro 2003]. After this model was developed, Major Paul Weaver, USMC, continued the work at NPS [Weaver 2004] with enhancements and an operational test of Rosenthal and Castro's "static optimization model" (along with a longer-range "dynamic model"). We shall refer to this last model as the "RCW model" hereafter.

The RCW model was tested at the Marine Corps Weapons and Tactics Instructor's (WTI) course. Although WTI has limited scope—specifically, it does not maintain a significant pool of unassigned aircraft at any time—the RCW model proved reasonably fast, and quite accurate and valuable [Weaver 2004]. The drawbacks to the RCW model, as it stood in 2004, were (a) the requirement for difficult-to-use optimization software and attendant licenses, and (b) "reasonably fast" might not be fast enough when dealing with a real ATO scenario. Chapter II will show that RAPT-OR must provide support for making a final decision in a three-minute window of the TST targeting process. This means that it must solve in seconds.

Our primary goal is to produce an immediately usable decision aid for ATO planners. In addition to the issues described above, one of the reasons that the RCW model has not yet been adopted for actual use is that prior research did not identify the ultimate end-users of the model. Consequently, the RCW model does not address all of the problems faced in rapid ATO planning. This thesis identifies the potential users of RAPT-OR, and provides a detailed study of where time-sensitive targeting occurs. We provide some background on potential users and the process by which an ATO is formulated and executed, and the specific challenges with regard to TSTs. To accomplish this, we have visited two separate AOCs as well as the facility that is responsible for training AOC personnel (505th Training Squadron, Hurlburt Field, Florida). In addition, we have observed six separate TST exercises to elicit input from potential operators of RAPT-OR.

D. SCOPE AND LIMITATIONS

Opportunities to test decision aids such as RAPT-OR are limited. A realistic operational test would have to take place in an AOC.

As mentioned above, RAPT-OR does not capture concerns for deconfliction. While deconfliction is an important consideration, we feel that this is primarily an air-space coordination problem and not within the scope of this thesis or RAPT-OR. On the other hand, RAPT-OR produces solutions so quickly, it should be possible to use it iteratively until an ATO revision is found that satisfies deconfliction requirements.

Certain AOC personnel have requested the ability to incorporate collateral damage estimates (CDEs) into the re-planning process. It is certainly possible to calculate a CDE for any strike package, and penalize each packages as an increasing function of this value. However, these calculations would require collection of vast amount of data to which we did not have access: incorporating CDEs within RAPT-OR is a field for future research.

E. THESIS ORGANIZATION

Chapter II provides a more thorough discussion of the AOC and the time-sensitive targeting process, as well as the billet(s) that would benefit most from the use of RAPT-OR. Chapter III describes the RAPT-OR optimization model as well as the heuristic used to solve it approximately. Chapter IV provides a detailed analysis and comparison of the RCW model and exact and heuristic solutions to the RAPT-OR model. Chapter V is devoted to conclusions and recommendations.

Appendix A describes modification to the RAPT-OR optimization model that will produce multiple courses of action. By implementing this embellishment, a decision maker could choose from a list of reformulated ATOs in descending order of quality and reject any that do not meet criteria not built into the model, e.g., deconfliction.

II. TIME SENSITIVE TARGETING IN THE AIR OPERATIONS CENTER (AOC)

A. INTRODUCTION

An AOC is "A jointly staffed facility established for planning, directing, and executing joint air operations in support of the joint force commander's operation or campaign objectives…."(JP 1-02 DOD Dictionary). This chapter describes the AOC, which is the organization responsible for the planning, production, dissemination and execution of an ATO. The AOC is also responsible for revising the ATO to prosecute TSTs. With a thorough understanding of the structure of an AOC and the complexity of the ATO process, the reader can understand the challenges associated with rapidly revising the ATO to accommodate TSTs. We will describe the compressed time cycle in which the reformulation of the ATO must occur, which clearly identifies the need for an automated decision aid.

We note that the reader who is familiar with the operations of an AOC may wish to proceed directly to section C for a description of the ATO production process.

B. ROLE AND RESPONSIBILITY OF THE AOC

Decision-making authority is central to the process of time sensitive targeting. The AOC is commanded by the Joint Force Air Component Commander (JFACC). The JFACC is designated by the JFC as the senior commander with the preponderance of air assets and the capability for command and control of these assets. The JFACC derives authority from the JFC [JP 3-30]. The JFACC advises the JFC on how he can best support the joint force with air and space assets. This advice includes the recommendation of targets to be classified as TSTs, and thus requiring a revision of the current ATO.

The AOC provides command and control (C2) for the theater joint aviation assets; however, some aviation assets may remain under the tasking authority of component commanders other than the JFACC. As the commander for all joint forces in a given theater, the JFC alone has authority for redirection of aviation assets. To enable a rapid targeting cycle for TSTs, the JFC often delegates TST engagement authority to the JFACC. Thus, the AOC becomes the central C2 agency for time sensitive targeting.

An AOC exists wherever there is a standing or potential joint force, for example: Republic of Korea (Korean Peninsula), Italy (Balkans), and Qatar (Iraq and Afghanistan). An AOC staff is comprised of all services and several national agencies. To execute theater-level C2 during 24-hour operations with subject-matter experts from many areas (e.g., pilots, targeteers, lawyers), each AOC is manned by hundreds of personnel. (Unfortunately, large, diverse staffs often hinder quick decision-making.)

To refine the process of guidance, production, execution and analysis of results for the ATO, the AOC is divided into five divisions: Strategy, Combat Operations, Combat Plans, Intelligence Surveillance Reconnaissance (ISR) and Air Mobility. Each division has important functions that the reader should understand, because they create an appreciation for the level of planning and consideration that goes into formulating an ATO and the difficulty of time-sensitive targeting. These functions also show how the various divisions will have influence on or will be influenced by RAPT-OR, should RAPT-OR be adopted.

The Strategy division formulates the Air Operations Directive (AOD) to ensure that the ATO is consistent with guidance from the JFACC, including guidance on TSTs. This division also employs an operations-research cell to carry out a post-execution assessment of each day's ATO. This cell reports to the Strategy division leader on how given strategies are working with respect to overall campaign objectives. Strategy is also responsible for taking JFC's guidance with respect to the prosecution of TSTs and ensuring that it is translated into the ATO. Because of this, the Strategy division would provide target values and other parameters required by the RAPT-OR model.

The Combat Plans division performs many tasks. Among Combat Plans' sub-elements is the joint or combined guidance, apportionment and targeting team (GAT or JGAT), and the master air attack planning (MAAP) cell. The job of the GAT is to produce the daily Joint Integrated Prioritized Target List (JIPTL). Once the JIPTL is approved by the JFACC, it then goes to the MAAP cell to have air assets assigned to targets. The MAAP assigns available weapons-delivery platforms to targets. During the MAAP and GAT portions of the ATO process, each target is assigned a priority and assets: these priorities would guide RAPT-OR in re-tasking existing targets.

Combat Operations is responsible for executing the ATO. To accomplish this, Combat Operations contains both offensive and defensive operations teams consisting of military aviators. It is the Offensive Operations team that prosecutes TSTs and may even include a special cell that for this purpose. We believe that the appropriate user of RAPT-OR, as the AOC is currently configured, resides in the Offensive Operations team. The Offensive Operations team would input the TSTs into RAPT-OR and specify the desired probabilities of kill, per the guidance of JFACC or JFC as supplied by the Strategy division.

The Intelligence, Surveillance and Reconnaissance (ISR) division and Air Mobility division support the other planning and execution divisions within the AOC with the addition of critical intelligence and air movement (logistics) information. ISR would provide the intelligence necessary to generate accurate probabilities of kill and attrition for use by RAPT-OR.

Figure 1 summarizes the discussion of all the divisions, teams and cells within the AOC.

<table>
<tr><th>Strategy</th><th>Combat Plans</th><th>Combat Ops</th><th>ISR</th><th>Air Mobility</th></tr>
<tr><td colspan="5">Core Teams</td></tr>
<tr><td>Strategy Plans Team</td><td>GAT Team</td><td>Offensive Operations Team</td><td>Analysis, Correlation and Fusion Team</td><td>Air Mobility Element</td></tr>
<tr><td>Operational Assessment Team</td><td>MAAP Team</td><td>Defensive Operations Team</td><td>Targeting/BDA Team</td><td>Airlift Control Team</td></tr>
<tr><td rowspan="2"></td><td>C2 Planning Team</td><td rowspan="2"></td><td>PED Team</td><td>Air Refueling Control Team</td></tr>
<tr><td>ATO Production Team</td><td>SCI Management Team</td><td>Aeromedical Evacuation Team</td></tr>
</table>

Figure 1. The Air Operations Center Organization, graphically.

RAPT-OR is designed for use by individuals within the Offensive Operations team of Combat Operations, although organizations in italics would need to supply specific input.

C. THE ATO PRODUCTION PROCESS

The production of the ATO is deliberative, and can only consider a target whose location is known. However, contingency missions are included for targets, time-sensitive or otherwise, that invariably appear during execution of the ATO. For instance, multiple groups of two to four aircraft may be assigned to "on-call close air support." See Figure 2 for an example of an ATO containing such a mission. RAPT-OR assigns each contingency mission to a dummy target, and does not view a change in that assignment as adding turbulence to a revised ATO.

ATO production begins 48 hours before the ATO is to be executed. All five AOC divisions remain engaged continuously in either production or analysis. Five ATOs are considered by the AOC at any one time. The first ATO resides with the Strategy division which develops the AOD; the second is in the guidance and apportionment process; the third is in master air attack development; the fourth ATO is being executed by Combat Operations; and the fifth is being assessed by the Strategy division's assessment team. In the end, the ATO production must integrate all elements of the air operation: airspace, air defense, in-flight refueling plan, communication plan, electronic warfare, search and rescue, suppression of enemy air defense, special instructions and rules of engagement.

The result of the above process is a static document, the ATO. Clearly this presents a problem for time-sensitive targeting. Targets that appear outside of the ATO production process must be dealt with immediately and must therefore be handled as exceptions to this process.

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TASKUNIT/2MAW VMA-231/ICAO:KNKT//
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AMSNDAT/0131D/-/AN/-/ESC//
MSNACFT/2/ACTYP:F14A/BEAK 31/2P2S2/FAMMO/20131/30131//
ARINFO/GRAPE 11/4011A/34011/NAME:ORANGE TRACK/200/ARCT:010815Z
/NDAR:010845ZOCT/KLBS:20.0/PFREQ:323.3/SFREQ:242.8/ACTYP:KC135/CDT/3
/TNKR:1/29-92/3-3-4//
MSNACFT/1/ACTYP:EA6B/CLAW 71/HARM/PODS/20171/30171//
ARINFO/APPLE 20/4010A/34010/NAME:BLUE TRACK/200/ARCT:010815Z
/NDAR:010845ZOCT/KLBS:20.0/PFREQ:343.3/SFREQ:277.8/ACTYP:KC10/CDT/2
/TNKR:2/18-81/2-2-3//
```

Figure 2. A sample from an ATO.

Starting at the first "TASKUNIT" we see that SHANK 71 is a flight of 2 AV-8Bs from the 2nd Marine Air Wing at Marine Corps Air Station, Cherry Point, NC. They are tasked with the mission of "XCAS" (airborne, on call, close air support) and should be on station with a load of MK-82 bombs. SHANK 71's aerial refueling information is located on the following lines, 4, 5 and 6 from the top.

D. TIME-SENSITIVE TARGETING

There are several challenges in time-sensitive targeting, the main one being that the timeline for targeting is now greatly compressed, yet all steps in the regular targeting process must still be accomplished. The JFC must quickly select an asset to strike this emergent target based on the six factors discussed in Chapter I: effectiveness, responsiveness, range, accuracy, threat and deconfliction.

TST targeting requires strike platforms that have the right mix of effectiveness, responsiveness, range and accuracy. Aircraft often possess that mix, so they are the most commonly used platform for striking TSTs, either solely or as part of an integrated strike with ground forces. Once the decision is made to task aircraft to strike a TST, command and control authority to enact that strike is passed from JFC to JFACC and the AOC.

Regardless of the urgent nature of a TST, the AOC must complete the same planning cycle for assigning strike assets as is required during the normal ATO planning process. This compressed targeting process is known as "dynamic targeting" and must satisfy six requirements, in rapid succession, in what is called the "kill chain": find, fix, track, target, engage and assess; see Figure 3.

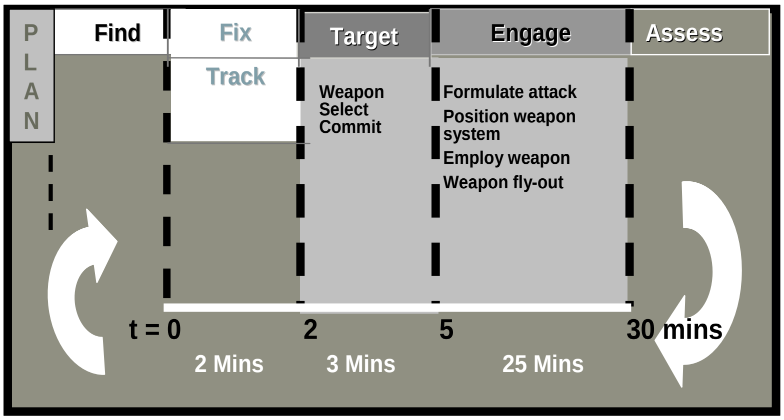

Figure 3. A diagram that indicates the amount of time allotted to each phase of the "Joint Kill Chain," referred to as Find-Fix-Track-Target-Engage-Assess (F2T2EA).
This thesis focuses on the "Target" phase, seeking to render one or more courses of action within three minutes.

Thirty minutes is the goal for dynamic targeting within the AOC, from "fix" (two minutes), to "target" (three minutes) to "engage" (25 minutes). That is, only one-half hour should elapse from the time a TST is accurately located until weapons impact; see Figure 3. This thesis focuses on the three-minute targeting step in this thirty-minute window. A decision aid that could not generate a course of action, or several, in the allotted three minutes would not be useful. As of this writing, RAPT-OR is the only analytical computational decision aid that can accomplish this task.

III. OPTIMIZATION MODEL FOR THE RETASKING OF AIR STRIKE ASSETS

A. INTRODUCTION

This chapter formulates the TST target-assignment problem as generalized set-packing problem. This integer program is called "RAPT-OR-IP." As background, we also discuss the models designed by Castro [2003] and Weaver [2004].

The model generator for RAPT-OR-IP (a) strips target assignments from the missions defined by the current ATO, (b) enumerates collections of these "targetless missions," and (c) combines those with targets to form a large set of potential strike packages. The model then assigns a "reward" to each strike package that accounts for the target value along with penalties for distance traveled by the package's aircraft, changes that package incurs over the current ATO, and other factors. The solution selects a subset of the potential strike packages that satisfies logical requirements and optimizes the revised ATO's overall reward. This chapter provides the formulation of RAPT-OR-IP, and describes the fast heuristic that we have developed to solve this model approximately.

B. AN INTEGER PROGRAM TO OPTIMIZE ATO REVISIONS

The following integer program, RAPT-OR-IP, seeks the best achievable revision to an incumbent ATO. After we present this simple-looking model, we develop the considerable detail required compute its objective-function coefficients and actually generate instances of the model.

1. Indices

$t \in T$ target (includes "none")

$m \in M$ ATO mission; a flight of one or more identical aircraft (typically with identical loadouts)

$\hat{m} \in \hat{M}$ ATO mission with target identification stripped: ("Mission" in quotes refers to a targetless mission.)

$p \in P$ (potential) strike package, consisting of one or more missions

$P_t \subseteq P$ subset of strike packages designed to strike target t

$P_{\hat{m}} \subseteq P$ subset of strike packages that include "mission" $\hat{m}$

2. Given Data [units]

$reward_p$ "reward" received if target strike package p is selected (includes factors for target value, expected attrition, distance and mission-to-target changes) [reward units]

$m\_changes_p$ number of mission-to-target changes that are incurred by selection of strike package p [cardinality]

$\overline{changes}$ maximum number of mission changes between the incumbent ATO and any revised ATO [cardinality]

3. Decision Variables

$STRIKE_p$ equals 1 if package p is selected, and is 0 otherwise

4. Formulation (RAPT-OR-IP)

$$\max_{STRIKE} \quad \sum_{p \in P} reward_p STRIKE_p \qquad (0)$$

$$\text{s.t.} \quad \sum_{p \in P_t} STRIKE_p \le 1 \qquad \forall t \in T \qquad (1)$$

$$\sum_{p \in P_{\hat{m}}} STRIKE_p \le 1 \qquad \forall \hat{m} \in \hat{M} \qquad (2)$$

$$\sum_{p \in P} m\_changes_p STRIKE_p \le \overline{changes} \qquad (3)$$

$$STRIKE_p \in \{0,1\} \qquad \forall p \in P \qquad (4)$$

5. Discussion

The objective (0) expresses the total reward received by the revised ATO. Constraints (1) allow each target to be attacked by at most one strike package. Constraints (2) allow a mission to be used in at most one strike package. Constraint (3) limits the number of mission-to-target changes between the incumbent ATO and the revised ATO; this constraint is optional, of course.

6. Data Development

Generating a realistic instance of RAPT-OR-IP depends on considerable exogenous data processing. We present this now.

a. Additional Indices

$a \in A$	aircraft type (e.g., AV-8BB, F-15C)
$r \in R$	threat type (e.g., SA6, SA10, or none)
$w \in W$	weapon type (e.g., MK-83, GBU-16)
$a(\hat{m})$	aircraft type of "mission" $\hat{m}$
$t(p)$	package p's target
$r(t)$	air-to-surface threat type presented by target t
$\hat{M}_p \subseteq \hat{M}$	subset of "missions" included in strike plan p
$\hat{t}(\hat{m})$	incumbent target for "mission" $\hat{m}$

b. Input Data [units]

$maxMissions$	maximum number of "missions" considered for any candidate strike package
$pk\_required_t$	commander's minimum required probability of killing target t
$numac_{\hat{m}}$	number of aircraft in "mission" $\hat{m}$
$config_{\hat{m},w}$	number of type w weapons carried by each aircraft in "mission" $\hat{m}$, called "loadout" or "standard conventional load" [weapons]
$ssp\_suppress_{w,r}$	single-shot probability that weapon w will suppress threat r
$ssp\_survive_{r,a}$	single-shot probability that aircraft a will survive threat r (we assume a threat will shoot once at each attacking aircraft in a mission)
$ssp\_kill_{w,t}$	single-shot probability that a weapon w will kill target t
$priority_t$	commander's priority for target t; highest = 1
$pri\_exponent$	shape parameter in target priority valuation
$priority\_wgt$	weight assigned to target-priority in objective
$attrition\_wgt$	weight assigned to attrition of friendly aircraft in objective
$distance_{\hat{m},t}$	distance in nautical miles from current position of "mission" $\hat{m}$ and target t
$distance\_wgt$	distance-penalty weighting factor in objective function
$change\_wgt$	mission-change-penalty weighting factor in objective function

7. Exogenous Computation

This section describes how we compute the objective-function coefficients, $reward_p$, for RAPT-OR-IP. Both Castro [2003] and Weaver [2004] use similar definitions and calculations, although their models and final objective-function coefficients are somewhat different.

Each "mission" in the set of available "missions" $\hat{M}$ is defined by the state of its constituent aircraft at the time of revision planning, but the planner can screen out missions that should not be revised. An "admissible package" meets certain criteria set by the decision maker with respect to acceptable probability of kill, package size and penalties. The planner has several controls to define admissibility, and therefore limit the enumeration of packages. (In its current implementation, RAPT-OR only limits admissibility through "*maxMissions,*" but other admissibility tests are trivial to implement.)

Strike packages are generated by enumerating each admissible combination of no more than *maxMissions* "missions." This is an important filter, because $|P| = \binom{|M|}{maxMissions}$ is possible.

The following computations are carried out for each potential strike package *p*. However, the final set of admissible packages P, includes only those potential packages that satisfy admissibility criteria. Note that each strike package *p* has target $t(p)$, so even though a target index may not appear in every expression indexed by *p*, it is defined.

$$m\_changes_p = \sum_{\substack{\hat{m} \in \hat{M}_p | \\ \hat{t}(\hat{m}) \neq t(p)}} 1;$$

$$numweps_{p,w} = \sum_{\hat{m} \in \hat{M}_p} numac_{\hat{m}} config_{\hat{m},w} \quad \forall w \in W;$$

$$p\_suppress_p = 1 - \prod_{\substack{w \in W_{\hat{m}}, \\ \hat{m} \in \hat{M}_p}} (1 - ssp\_suppress_{w,r(t(p))})^{numweps_{p,w}};$$

$$p\_attrit_p = (1 - p\_suppress_p) \times (1 - p\_survive_p);$$

$$p\_survive_p = 1 - \prod_{\hat{m} \in \hat{M}_p} (1 - ssp\_survive_{r(t(p)),a(\hat{m})})^{numac_{\hat{m}}};$$

$$p\_kill_p = 1 - \prod_{\substack{w \in W_{\hat{m}}, \\ \hat{m} \in \hat{M}_{\hat{p}}}} (1 - ssp\_kill_{w,t(p)})^{numweps_{p,w}} \text{; and}$$

$$p\_success_p = (1 - p\_attrit_p) \times p\_kill_p .$$

A strike package p is currently admissible in RAPT-OR if $p\_success_p > 0$. A stronger criterion on probability of success could be used, e.g., $p\_success_p \geq 0.5 \times pk\_required_{t(p)}$. This would reduce the number of admissible packages and thereby simplify the following computations. Other admissibility screens based on p_attrit_p or other values are also possible.

For an admissible strike package p,

$$target\_value_p = \min\left(p\_success_p, pk\_required_{t(p)}\right) \times priority\_wgt \times priority_{t(p)}^{-pri\_exponent};$$

$$pen\_attrit_p = attrit\_wgt \times p\_attrit_p;$$

$$pen\_distance_p = distance\_wgt \times \sum_{\hat{m} \in \hat{M}_p} numac_{\hat{m}} distance_{\hat{m},t(p)} \text{; and}$$

$$pen\_change_p = change\_wgt \times m\_Change_p .$$

Note that $target\_value_p$ is calculated such that the over-allocation of assets, or “overkill,” to a highly valued target does not result in an increase in $target\_value_p$.

Each objective-function coefficient $reward_p$ is a composite of target value and penalties:

$$reward_p = target\_value_p - pen\_attrit_p - pen\_distance_p - pen\_change_p .$$

We can solve the RAPT-OR IP with conventional, linear-programming based, integer-programming software, but we can also construct high-quality solutions very quickly with the purpose-built heuristic described next.

.

C. A FAST HEURISTIC SOLUTION METHOD

This section describes an intuitively appealing greedy heuristic that finds a feasible solution to RAPT-OR-IP in polynomial time.

1. Additional Indices

$p \in P^{OK} \subseteq P$	set of strike packages eligible for selection
$p^* \in P^* \subseteq P$	set of strike packages selected

Note that the solution $P^* = \varnothing$, i.e., $STRIKE \equiv 0$ is feasible in RAPT-OR-IP. We add strike packages to the set P^* while maintaining this feasibility.

2. RAPT-OR-GH (RAPT-OR, Greedy Heuristic)

Input: Data for RAPT-OR-IP.
Output: A set of strike package P^* that satisfies the constraints of the RAPT-OR IP and attempts to optimize that IP's objective function.

{

$P^{OK} = P$; $P^* = \varnothing$;

/*The next statement selects the feasible package with the highest reward*/

Select: $p^* = \underset{p \in P^{OK}}{\text{argmax}} \left\{ reward_p \right\};$

/* Reject p^* if adding it to partial ATO P^* would cause too many changes */

If the number of changes in $P^* \cup \{p^*\}$ exceeds $m\_Changes$ {

$P^{OK} = P^{OK} \setminus \{p^*\};$

Go to Select;

}

/* Otherwise, p^* is added to the ATO */

$P^* = P^* \cup \{p^*\};$

/* If all targets are covered by the new ATO, the algorithm is finished */

If $|P^*| == |T|$ go to End;

/* p^* covers a previously uncovered target. Any remaining strike packages that cover that target can be eliminated from further consideration */

For (all $p \in P^{OK} \mid t(p) == t(p^*)$) $\left\{ P^{OK} = P^{OK} \setminus \{p\}; \right\}$

If $P^{OK} == \varnothing$ **go to** End;

Go to Select;

End: Print P^*;

}

RAPT-OR-GH has intuitive appeal and has proven effective in practice. If future testing shows that it performs inadequately on some problems, sophisticated heuristics are available for this problem. We refer the reader to Senju and Toyoda [1968] and Dobson [1982]; see also Brown et al. [1985] who apply the methods of those papers to generalized set-packing problems that resemble RAPT-OR-IP.

3. Graphical User Interface (GUI) and Improvements

For his investigation of time-sensitive targeting, Weaver [2004] uses a graphical user interface (GUI) developed by Mr. Anton Rowe. RAPT-OR uses an improved version of this GUI, developed by Rowe in consultation with the author [Rowe 2006]. Through the GUI, the user can accomplish these tasks:

1. Input the current ATO and manually include or exclude missions as desired.
2. Input TSTs, to include each target's priority, location, type, defenses and desired probability of kill.
3. Adjust model weights for priority, attrition and distance.
4. Specify a maximum number of missions that can be assigned to a single package. This parameter was added for this thesis work so that only packages of reasonable size would be generated.
5. (a) Select an exact solution to RAPT-OR-IP using GAMS optimization software, if available, or (b) use RAPT-OR-GH (heuristic solver) to obtain an approximate solution, or (c) do both, if possible.
6. Set the maximum number of mission changes allowed to the incumbent ATO.

4. Summary

We have extended the models of Castro [2003] and Weaver [2004] for revising ATOs to respond to time-sensitive targets. The new model, RAPT-OR-IP, prevents "overkill" of high-value targets at the risk of leaving other, lower priority targets un-struck. We have also developed a fast heuristic, RAPT-OR-GH, that produces high-quality solutions to RAPT-OR-IP. The size of the model is greatly reduced over its predecessors because packages are limited to a reasonable number of missions.

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IV. COMPUTATIONAL RESULTS

In order to validate RAPT-OR as a viable means of performing weapon-target pairing in real-time, we compare solutions produced by RAPT-OR-GH, RAPT-OR-IP and the legacy RCW model. All computations are carried out on a 2.0 GHz Pentium 4 Dell desktop computer at the Naval Postgraduate School.

A. INITIAL TEST SCENARIO

We perform initial tests on a simple scenario in which two TSTs must prosecuted during a time window in an ATO that involves six targets (SLA 15, SLA 30, TGT SA3, TGT 1, TGT 2 and TGT 3) and 11 missions; see Figure 4. The two TSTs that "pop up" are "Terrorist Dhow" and "Osama." The former is undefended while the latter is defended by an SA-6, which must be neutralized by an electronic attack aircraft (e.g., an EA-6B); see Figure 5.

ATO 19:45

Include	Avail	Mission	ETD	ETR	Base	#	Aircraft	Configuration	Assignment	Recommend
TRUE	FALSE	6111	18:51	20:07	Riyadh	2	AV8B	[2] CBU58	TGT SA3	
TRUE	FALSE	6113	18:51	20:07	Riyadh	2	F16	[4] MK83	TGT SA3	
TRUE	FALSE	6141	18:51	20:07	Riyadh	2	AV8B	[2] CBU58	TGT 2	
TRUE	FALSE	6143	18:51	20:07	Riyadh	2	F16	[4] MK83	TGT 2	
TRUE	FALSE	6115	18:51	20:07	Al Ahsa	2	F16	[4] MK83	TGT 3	
TRUE	TRUE	6145	18:51	20:07	Al Ahsa	2	AV8B	[4] MK83	SLA 15	
TRUE	TRUE	6147	18:51	20:07	Al Ahsa	2	AV8B	[6] MK83	SLA 15	
TRUE	FALSE	6161	18:51	20:07	Al Ahsa	2	F15	[4] MK83	KB AA80	
TRUE	TRUE	6195	19:00	23:00	USS Roosevelt	2	F18C	[4] CBU58	SLA 15	
TRUE	TRUE	6196	19:00	23:00	USS Roosevelt	2	F18C	[4] CBU58	SLA 15	
TRUE	TRUE	6197	19:00	23:00	USS Roosevelt	2	EA6B	[1] POD [1] HARM	TGT SA3	
TRUE	TRUE	6101	19:19	22:09	Al Kharj	2	EA6B	[1] POD [1] HARM	TGT SA3	
TRUE	TRUE	6103	19:19	22:09	Al Kharj	1	EA6B	[1] POD [1] HARM	TGT 2	
TRUE	TRUE	6104	19:19	22:09	Al Kharj	1	EA6B	[1] POD [1] HARM	SLA 30	
TRUE	TRUE	6131	19:34	20:54	King Fahd	2	F15	[4] MK83	TGT 1	
TRUE	TRUE	6133	19:34	20:54	King Fahd	2	F15	[4] MK83	TGT 1	
TRUE	TRUE	6135	19:34	20:54	King Fahd	2	F15	[4] MK83	TGT 3	
TRUE	FALSE	6137	20:04	21:24	King Fahd	2	F18D	[4] MK83	KB AA80	
TRUE	FALSE	6175	20:49	22:09	King Fahd	2	F18D	[4] MK83	KB AA80	
TRUE	FALSE	6163	21:07	22:21	Riyadh	2	AV8B	[4] MK82	SLA 15	
TRUE	FALSE	6165	21:22	22:36	Riyadh	2	AV8B	[2] CBU58	SLA 15	

Figure 4. A screen shot from RAPT-OR that displays missions available on the test ATO.
The eleven shaded missions are those that are available for reassignment during the current time window and those that the user allows to be reassigned. ("Avail" indicates whether or not the mission could be reassigned, and "Include" indicates whether or not the user wants to a allow reassignment.) The column labeled "Assignment" shows the six targets currently assigned to those missions, viz., SLA 15, TGT SA3, TGT 2, SLA 30, TGT 1 and TGT 3.

Target List

Include	Target	Priority	Lat	Lon	Type	Threat	Desired Probability of Success	Estimated Probability of Success	Estimated Probability of Attrition
FALSE	TGT SA3	2	32.70	40.00	SA3	SA3	95%		
FALSE	TGT A	4	32.52	45.00	Logistics Site		95%		
FALSE	TGT 2	8	35.73	43.83	Assembly Area		95%		
FALSE	TGT 3	9	31.20	43.64	Assembly Area		95%		
FALSE	ZSU	5			ZSU	ZSU	75%		
FALSE	SA8	6			SA8	SA8	75%		
FALSE	FROG7	7			FROG7		75%		
TRUE	Osama	1	33.26	43.26	Troop in Open	SA6	75%		
TRUE	Terrorist Dhow	3	30.58	46.87	Civilian Watercraft		95%		

Figure 5. The Time Sensitive Target List from RAPT-OR.
This screen shot displays the current list of TSTs along with associated data. The user only wants to consider those TSTs having "TRUE" listed in the "Include" column, in this case, "Osama" and "Terrorist Dhow." This list will also report, in the last two columns, probability of success and attrition after revising the ATO.

Values for damage, attrition, success, suppression and distance are calculated in exactly the same way for both RAPT-OR-IP and the RCW model. This is not an endorsement of the independence assumption inherent in some of the calculations, but rather a standardized way of obtaining test results. RAPT-OR could use any function to calculate these values, including the use of standard table look-ups.

All penalties weights and factors are standardized between the two models; see Figure 6. RAPT-OR's parameter *maxMissions*, which specifies the maximum number of missions that a strike package may contain, is set to 5. This value cannot be limited in the RCW model.

Model Parameters

Parameter	Value
Priority Weight	1000
Priority Exponent	2
Attrition Weight	1
Change Weight	0.1
Distance Weight	0.001
Max Package	5
Start Time	18:30
Elapsed Minutes	58
Current Time	19:28

Figure 6. A screen shot of the parameters page in RAPT-OR. The first five values denote the parameters that are held in common between RAPT-OR and the RCW model in computational tests. The last three values simply define the time window of interest (in both models). Note that "Max Package" denotes RAPT-OR's parameter *maxMissions*, which does not influence computations in the RCW model.

B. INITIAL TEST RESULTS FOR RAPT-OR-GH

Test results for RAPT-OR-GH are conclusive and interesting. RAPT-OR-GH produces solutions for the test scenario in less than 2 seconds. In contrast, the RCW model requires 205 seconds (3 minutes and 25 seconds). This is important beyond the mere fact that RAPT-OR is faster: RAPT-OR's speed would give the Offensive Operations cell the opportunity to generate several alternative courses of action before the three-minute bell sounds. For instance, if the initial solution accepted too much risk, the Attack Coordinator could simply place a higher weight on the attrition penalty and rerun the model. The revised solution might eliminate some high-risk strikes entirely (because a high enough penalty might lead to the riskier packages having negative rewards), or the solution might accept lower success probabilities in order to reduce the chances for attrition.

Figure 7 shows the modified ATO produced by RAPT-OR-GH, and Figure 8 shows the corresponding results for the RCW model's ATO revision.

ATO 19:45

Include	Avail	Mission	ETD	ETR	Base	#	Aircraft	Configuration	Assignment	Recommend
TRUE	FALSE	6111	18:51	20:07	Riyadh	2	AV8B	[2] CBU58	TGT SA3	
TRUE	FALSE	6113	18:51	20:07	Riyadh	2	F16	[4] MK83	TGT SA3	
TRUE	FALSE	6141	18:51	20:07	Riyadh	2	AV8B	[2] CBU58	TGT 2	
TRUE	FALSE	6143	18:51	20:07	Riyadh	2	F16	[4] MK83	TGT 2	
TRUE	FALSE	6115	18:51	20:07	Al Ahsa	2	F16	[4] MK83	TGT 3	
TRUE	TRUE	6145	18:51	20:07	Al Ahsa	2	AV8B	[4] MK83	SLA 15	
TRUE	TRUE	6147	18:51	20:07	Al Ahsa	2	AV8B	[6] MK83	SLA 15	
TRUE	FALSE	6161	18:51	20:07	Al Ahsa	2	F15	[4] MK83	KB AA80	
TRUE	TRUE	6195	19:00	23:00	USS Roosevelt	2	F18C	[4] CBU58	SLA 15	Terrorist Dhow
TRUE	TRUE	6196	19:00	23:00	USS Roosevelt	2	F18C	[4] CBU58	SLA 15	
TRUE	TRUE	6197	19:00	23:00	USS Roosevelt	2	EA6B	[1] POD [1] HARM	TGT SA3	Osama
TRUE	TRUE	6101	19:19	22:09	Al Kharj	2	EA6B	[1] POD [1] HARM	TGT SA3	
TRUE	TRUE	6103	19:19	22:09	Al Kharj	1	EA6B	[1] POD [1] HARM	TGT 2	
TRUE	TRUE	6104	19:19	22:09	Al Kharj	1	EA6B	[1] POD [1] HARM	SLA 30	
TRUE	TRUE	6131	19:34	20:54	King Fahd	2	F15	[4] MK83	TGT 1	Osama
TRUE	TRUE	6133	19:34	20:54	King Fahd	2	F15	[4] MK83	TGT 1	
TRUE	TRUE	6135	19:34	20:54	King Fahd	2	F15	[4] MK83	TGT 3	
TRUE	FALSE	6137	20:04	21:24	King Fahd	2	F18D	[4] MK83	KB AA80	
TRUE	FALSE	6175	20:49	22:09	King Fahd	2	F18D	[4] MK83	KB AA80	
TRUE	FALSE	6163	21:07	22:21	Riyadh	2	AV8B	[4] MK82	SLA 15	
TRUE	FALSE	6165	21:22	22:36	Riyadh	2	AV8B	[2] CBU58	SLA 15	

Figure 7. The ATO annotated after recommendations are made in RAPT-OR.

Target List

Include	Target	Priority	Lat	Lon	Type	Threat	Desired Probability of Success	Estimated Probability of Success	Estimated Probability of Attrition
FALSE	TGT SA3	2	32.70	40.00	SA3	SA3	95%		
FALSE	TGT 1	4	32.52	45.00	Logistics Site		95%		
FALSE	TGT 2	8	35.73	43.83	Assembly Area		95%		
FALSE	TGT 3	9	31.20	43.64	Assembly Area		95%		
FALSE	ZSU	5			ZSU	ZSU	75%		
FALSE	SA8	6			SA8	SA8	75%		
FALSE	FROG7	7			FROG7		75%		
TRUE	Osama	1	33.26	43.26	Troop in Open	SA6	75%	94.2%	0.1%
TRUE	Terrorist Dhow	3	30.58	46.87	Civilian Watercraft		95%	99.9%	0.0%

Figure 8. The RAPT-OR "Target List" page displaying a solution from the test scenario, produced by RAPT-OR-GH.

The results here are analogous to those for RAPT-OR-GH. showing that both targets have been co with a 94.2% probability of success for "Osama" and 99.9% for "Terrorist Dhow."

Targets

Include	Target	Priority	Lat	Lon	Type	Threat	Probability of Success	Probability Achieved	Probability of Attrition
FALSE	TGT SA3	2	32.70	-112.62	SA3	SA3	95%		
FALSE	TGT 1	4	34.40	-112.08	Logistics Site		95%		
TRUE	Terrorist Dhow	3	32.00	-119.00	Civilian Watercraft		95%	98%	0%
FALSE	TGT 3	8	32.18	-112.40	Assembly Area		95%		
FALSE	ZSU	5			ZSU	ZSU	75%		
FALSE	SA8	6			SA8	SA8	75%		
FALSE	FROG7	7			FROG7		75%		
TRUE	Osama	1	32.34	-118.00	Troop in Open	SA6	75%	100%	0%

Figure 9. Results for the RCW model.

This target list is analogous to the Target List table for RAPT-OR. There are differences in the location columns (Lat, Lon) because the scenario for the RCW test was set up in a different location in the world. However, all relative locations and distances remain the same between the two scenario representations.

As mentioned in Chapter III, we designed RAPT-OR to create packages as close to the user-mandated probability of success, without being less than that number. Because of this embedded logic, RAPT-OR sees no benefit in over-kill of the highest priority targets. This explains the above results: while both models chose the same aircraft from the ATO, they assign them differently. Both RAPT-OR and the RCW model send the same EA-6B to mitigate Osama's SA-6, but RAPT-OR assigns an F-18 with smaller weapons to attack Osama because the pre-defined success criterion for Osama is only 75% probability of kill. In contrast, the RCW model allots larger weapons to Osama due to his priority and the fact that higher probability of kill does yield a greater reward in that model. In effect, the way that RAPT-OR calculates penalties and rewards embodies the military axiom of "economy of force" and husbands assets for other potential targets and those assigned on the ATO (Figure 10). Through this mechanism RAPT-OR produces a solution that is closer to commander's intent than the legacy model.

C. COMPARING RAPT-OR-GH AND RAPT-OR-IP

We believe that a majority of future RAPT-OR users will be operating without the aid of commercial optimization software, so it is imperative to show that the greedy heuristic, RAPT-OR-GH, generates near-optimal solutions in real-time. For this purpose, Table 1 compares heuristic and optimal solutions for six scenarios of varying sizes.

In all cases except the last, GH finds the same solution as IP, i.e., in five of six cases, heuristic produces the optimal solution. In the one case that the optimal solution is slightly better than the heuristic one, the difference is only 0.02%. Apparently, the heuristic obtains a solution that gives a better response time (smaller distance penalty) while sacrificing in probability of success.

Solution times for both GH and IP are short (a fraction of a second versus several seconds, respectively), and are not listed. We believe that further testing on larger problems will show the computational-speed advantage of RAPT-OR-GH, but we must leave this for future research.

No. of Missions	Total No. of Targets	Number of TSTs	Obj. Function Value		Prob. of Success		Prob. of Attrition	
			GH	Exact	GH	Exact	GH	Exact
8	4	1	10.92	10.92	.974	.974	0.0	0.0
8	4	2	110.14	110.14	.918	.918	0.1	0.1
11	5	3	134.25	134.25	.893	.893	0.1	0.1
14	6	4	140.17	140.17	.893	.893	0.1	0.1
16	8	3	116.01	116.01	.918	.918	0.1	0.1
20	9	4	140.58	140.61	.696	.747	0.1	0.1

Table 1. Tests comparing heuristically generated and optimal solutions for RAPT-OR-IP.

This table shows that RAPT-OR-GH's heuristic solution ("GH" versus "Exact") is optimal in five of six test scenarios. In the last scenario, the heuristic solution is still within 0.02% of being optimal. (Solution times are not listed because neither GH nor the exact solution require more than a few seconds to solve any of these problems.)

V. CONCLUSIONS AND NEW OPPORTUNITIES

A. SUMMARY

This thesis has described RAPT-OR (Rapid Asset Pairing Tool-Operations Research), an automated decision aid for weapon-target pairing in the case of a time-sensitive target. RAPT-OR comprises a set-packing optimization model and generator, a heuristic solver, an optional exact solver, a database and a graphical user interface (GUI). We show that RAPT-OR is the only tool available for making near-optimal, real-time revisions to an Air Tasking Order to accommodate time-sensitive targets (TSTs).

B. DIRECT OPERATIONAL APPLICATION

During the writing of this thesis, airpower was used to neutralize a significant terrorist threat in the Iraqi area of operations, Abu Musab al-Zarqawi. In this example, we saw ground forces find, fix and track a textbook TST. The offensive operations cell in the Air Operations Center at Al Udeid Air Base, Qatar, then targeted this TST with two F-16s carrying precision-guided munitions, but they did so without the aid of an analytical decision aid. The Zarqawi attack may be viewed as a success for the current time-sensitive targeting process, but the same conflict contains examples of failures, too. This thesis describes and demonstrates an automated decision aid that will reduce the number of future failures.

B. OPERATIONAL INTRODUCTION

RAPT-OR has been briefed to a number of different agencies and individuals. These include the U.S. Air Force Command and Control Innovation Task Force, the Navy Warfare Development Command, the Joint-Fires integrated project team at the Naval Postgraduate School, students and instructors of the United States Air Force's 505th Training Squadron (TRS), the Combined Air Operations Center: Osan, Korea and U.S. Navy Director of Assessments (N81). Of particular note is the visit to the 505th

TRS, because this is where personnel for all U.S. AOCs are trained for follow-on assignment around the world. Several of the student officers were going on to be Attack Coordinators in an active AOC and voiced interest in RAPT-OR for immediate use in operational theaters. However, since RAPT-OR's full contribution cannot be realized without DoD-wide acceptance and support, we introduced RAPT-OR to several standardization organizations for more complete acceptance and support before fielding. The members of all these organizations did have several insightful comments and suggestions for enhancing RAPT-OR.

C. FUTURE DEVELOPMENT

After introducing RAPT-OR to several potential customers within DoD, the suggestions listed below were made to make RAPT-OR more useful.

1. Alternate Courses of Action

This enhancement would automatically provide alternate ATO revisions that vary weights on risk, probability of kill, replanning turbulence and other factors, and provide alternate ATO revisions   This would be very easy to implement. Currently, if the user has the right commercial optimization software, he or she can already generate alternate courses of action that yield decreasing levels of "quality" for a fixed set of weights. This could be used to quickly search for solutions that satisfy secondary criteria, regarding, for instance, deconfliction.

2. Interface with the Joint Munitions Effectiveness Manual (JMEM)

JMEM is a classified document that includes, among other things, actual probabilities of kill given a specific delivery profile and delivery platform. By interfacing with JMEM, RAPT-OR would have correct, classified attrition and damage probabilities for all weapons and weapon systems. In addition, this would eliminate the simple linearity and independence assumptions currently used in RAPT-OR's calculations of probability of damage and attrition.

3. Interface with the Common Operating Picture (TBMCS or JBMC2)

RAPT-OR should interface with current and future common operating picture (COP) software. This would enable RAPT-OR to more accurate solutions, since aircraft position and available remaining weapons would be updated in real time. The current system is known as Theater Battle Management Core System (TBMCS) and its successor is in development: Joint Battle Management Command and Control (JBMC2)

4. Expand RAPT-OR to all Fire Support Assets

In chapter I of this thesis, examples were given of all the fire-support assets that the JFC had at his/her disposal when contemplating the prosecution of a TST; airpower was not alone. We feel that with minimal effort RAPT-OR could be expanded to include all airborne, surface and sub-surface fire support assets in a theater, and give the JFC the best possible asset choice. As the U.S. military continues its push towards a smaller, lighter and more distributed force, the command and control of this force must adapt to be able to cope with the increase in fire support requests from a much higher number of customers: RAPT-OR could give fire-support coordinators this capability. It is in this effort that we feel RAPT-OR could make its greatest contribution. As an example, the United States Marine Corps is now fielding the “distributed operations” concept, which involves the discretizing of larger units into many more small, highly-mobile units. However, the Marine Corps has not developed a way to source these small, dispersed units with the fire support that they will need in the future: RAPT-OR is a solution.

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APPENDIX A

Generating alternative courses of action via commercial optimization software.

We can report optimal ATO revisions in decreasing order of optimality as follows:

Indices

$k \in K$ indexes potential ATO revisions that have already been reported

Data

$strike^*_{k,p}$ 1 if already-reported ATO revision k includes package p, else 0

Formulation (append to constraints (1)-(4) of RAPT-OR-IP)

$$\sum_{p \in P | strike^*_{k,p}=1} STRIKE_p + \sum_{p \in P | strike^*_{k,p}=0} (1 - STRIKE_p) \geq 1 \qquad \forall k \in K \qquad (5)$$

Discussion

Each constraint (5) excludes respective strike plan $k \in K$. To use this feature, RAPT-OR-IP, with constraints (5), would be solved with $K = \varnothing$ to obtain $strike^*_{1,p}$. That solution would define $K = \{1\}$, RAPT-OR-IP would be solved with the new K for $strike^*_{2,p}$, $K = \{1,2\}$ would now be defined, and the process repeated. This process could be stopped at any point determined by the user.

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