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**NAVAL  
POSTGRADUATE  
SCHOOL**

**MONTEREY, CALIFORNIA**

**THESIS**

**OPTIMIZING MARINE SECURITY GUARD  
ASSIGNMENTS**

by

Maro D. Enoka

June 2011

Thesis Advisor:  
Second Reader:

Emily M. Craparo  
W. Matthew Carlyle

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**OPTIMIZING MARINE SECURITY GUARD ASSIGNMENTS**

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Submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE IN OPERATIONS RESEARCH**

from the

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## **ABSTRACT**

The Marine Corps Embassy Security Group (MCECG) assigns 1,500 Marine Security Guards (MSGs) to 149 embassy detachments annually. While attempting to fulfill several billet requirements, MCECG strives to balance MSG experience levels at each embassy detachment and assign MSGs to their preferred posts. The current assignment process is accomplished manually by three Marines and takes more than 6,000 hours per year. This thesis presents the Marine Security Guard Assignment Tool (MSGAT). MSGAT is an Excel-based decision support tool that utilizes a system of workbooks to guide MCECG through a streamlined data collection and provide optimal assignments. MSGAT assignments result in a higher satisfaction when compared with manual assignments. MSGAT has had an immediate and quantifiable impact on the assignment process. It has reduced person-hours by 80%, increased overall assignment quality and efficiency and improved the operational readiness of MCECG by optimizing MSG assignments.



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# LIST OF ACRONYMS AND ABBREVIATIONS

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A/	Assistant Detachment Commander
AOR	Area of Responsibility
ASMOD	Assignment Modification Formulation
BALMOD	Balance Model Formulation
BRAC	Base Realignment and Closure
CSV	Comma-Separated-Value
CO	Company or Region Command
COIN-MP	Computational Infrastructure - Mixed Program
COIN-OR	Computational Infrastructure for Operations Research
DC	Designated Country
DCTB	Date Current Tour Began
DetCmdr	Detachment Commander
DIC	Detachment Identification Code
DLL	Dynamic Linked Library
DOR	Date of Rank
DoS	Department of State
EAM-GLOBAL	Enlisted Assignment Model - Global
FY	Fiscal Year
GOS	Good of the Service
HQ	Headquarters
HQMC	Headquarters Marine Corps



MARADMIN	Marine Administrative Message
MARS	Manpower Assignment Recommendation System
MCB	Marine Corps Base
MCC	Marine Command Code
MCEITS	Marine Corps Enterprise Information Technology Services
MCESG	Marine Corps Embassy Security Group
MCMS	Marine Corps Manpower System
MCTFS	Marine Corps Total Force System
MSG	Marine Security Guard
MSGAT	Marine Security Guard Assignment Tool
MOE	Measure of Effectiveness
MOS	Marine Occupational Specialty
NMCI	Navy-Marine Corps Internet
NPS	Naval Postgraduate School
OCPS	Officer Career Path Selection
OPC	Off Program Completely
OR	Operations Research
OSAF	Optimally Stationing Army Forces
PLT	Platoon or Embassy Detachment
RFC	Removed for Cause
RTD	Rotation Tour Date
SCASMOD	Single Commodity Assignment Modification Formulation
SSgt	Staff Sergeant

SINGCOM	Single Commodity Formulation
T/O	Table of Organization
TBD	To Be Determined
TBS	The Basic School
U.S.	United States
USMC	United States Marine Corps
VBA	Visual Basic for Applications
WASR	Wartime Authorized Strength Report
WOSF	Wartime Officer Slate File

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# EXECUTIVE SUMMARY

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The Marine Corps Embassy Security Group (MCECG) is responsible for assigning 1,500 Marine Security Guards (MSG) to 149 embassy detachments annually. MSG duty is a three-year tour in which MSGs typically serve at three embassies for one year apiece. In order to maintain continuity at the embassies, there are five assignment cycles per year, each of which involves rotation of 300 MSGs. While attempting to fulfill several billet requirements, MCECG simultaneously strives to balance MSG experience levels at each embassy detachment and assign MSGs to their preferred posts. The current assignment process is undertaken manually by three Marines and requires about 1,200 person-hours per cycle. The manually-generated assignments result in a low satisfaction at all levels — at MCECG, at regional headquarters, and among individual MSGs.

This thesis presents the Marine Security Guard Assignment Tool (MSGAT). MSGAT is an Excel-based decision support tool that utilizes a system of workbooks to guide MCECG through a streamlined data collection and assignment process. The tool implements an integer linear program to provide an optimal assignment of MSGs to billets. MSGAT allows the user to prioritize MCECG requirements, needs of the embassies, and desires of individual MSGs. MSGAT also allows the user to modify an existing assignment while maintaining a desired degree of persistence via a second integer linear program.

The integer linear program utilized by MSGAT is implemented via solvers from the Computational Infrastructure for Operations Research (COIN-OR) project. The COIN-OR project provides open-source optimization software compatible with the Microsoft Office suite and the Navy-Marine Corps Internet (NMCI).

To validate MSGAT and illustrate its usefulness in the assignment cycle, this thesis compares assignments generated by MSGAT with manually-generated assignments using historical data obtained from MCECG for five previous assignment cycles. MSGAT assignments perform significantly better with respect to several MCECG-identified measures of effectiveness (MOEs) than manual assignments, and they result in a higher satisfaction among all Marines.

In addition to outperforming manual assignment solutions with respect to the MOEs, MSGAT has significantly reduced the amount of time required to execute an assignment cycle. It has reduced person-hours by 80%, from 1,200 hours per cycle to 240 hours. Moreover, MSGAT has reduced the assignment calculation time from 3 weeks down to approximately 30 seconds.

As of June 2011, MSGAT is currently in use at MCEG. The data collection functionality of MSGAT was used to collect MSG and billet information for the creation of the Scrub List, Post Requirements, and Post Choices documents during the third and fourth assignment cycles of fiscal year 2011 (assignment cycles 3-11 and 4-11). Additionally, MSGAT will be calculating assignment solutions alongside the MCEG assignments section during the 4-11 assignment cycle. Solutions achieved by MSGAT are expected to be implemented by MCEG. Full MSGAT implementation is forecasted for the fifth assignment cycle of fiscal year 2011, the 5-11 assignment cycle. Data collection for this cycle begins in July 2011.

MSGAT has had an immediate and quantifiable impact on the MSG assignment process at MCEG. It has reduced person-hours required to produce an assignment, increased overall accuracy and efficiency and improved the operational readiness of MCEG by optimizing the assignment of MSGs to United States embassies.

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# CHAPTER 1:

## INTRODUCTION

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### **1.1 Problem**

The Marine Security Guard (MSG) program, in its current form, has been in place since December, 1948. MSGs are responsible for providing “internal security services at designated United States (U.S.) Diplomatic and Consular facilities to prevent the compromise of classified information and equipment that is vital to national security,” (DoS 1999). These Marines currently serve at 149 embassies and consular facilities, henceforth referred to as detachments. The detachments are partitioned into nine Marine Corps Embassy Security Group (MCESG) Region Commands consisting of six to twenty-five MSG billets each.

MCESG Region Commands report to MCESG Headquarters and are responsible for exercising command of Marines assigned to MSG detachments within their respective region (DoS 1999). MCESG Headquarters exercises administrative control over MSGs. Among other issues, administrative control involves coordinating the assignment of MSGs to detachments. Administrative control also involves ensuring that MSGs maintain required qualifications, coordinating personnel assignments, and logistics support.

In June of 2010, MCESG approached the Naval Postgraduate School (NPS) Operations Research (OR) department for assistance in streamlining the process of assigning MSGs to detachments. Currently, assignment personnel at MCESG manually assign 1,200 to 1,500 enlisted Marines each year to available billets within detachments. The MSG assignment problem considers a number of hard and soft constraints and is very labor intensive. Although the manual assignment process produces feasible solutions, no guarantees are made concerning the quality of these solutions.

This thesis leverages optimization techniques to develop a decision support tool, the Marine Security Guard Assignment Tool (MSGAT). The goal of MSGAT is to expedite the assignment cycle while maintaining or improving solution quality relative to manual assignment.

The MSG assignment problem is addressed using two integer linear programs that seek to optimize the overall quality of fit of the assignments made. Quality of fit is determined by MCESG-identified directives, which are described in the next chapter. Additionally, MSGAT streamlines



the flow of information between the detachments, region commands, and MCESG Headquarters in order to facilitate creation of a properly formatted, all-inclusive input database.

This thesis also compares assignments generated by MSGAT with five assignments created manually by the MCESG Assignments Section in 2010 and 2011. As Chapter 4 demonstrates, MSGAT produces excellent assignments with respect to all measures of effectiveness (MOEs) identified through MCESG directives.

This project has had an immediate and quantifiable impact on the efficiency and effectiveness of the assignment process — MSGAT is to be used at least five times a year by assignment personnel at MCESG. An optimal solution saves many person-hours of work and allows the MCESG staff to explore several options for each assignment cycle. MSGAT will not replace MCESG assignment personnel; rather, it will provide a good initial assignment (or several assignments) that can serve as a starting point for MCESG.

## **1.2 Background**

### **1.2.1 History**

The MSG program began with the Foreign Service Act of 1946. This act declared, “the Secretary of the Navy is authorized, upon the request of the Secretary of State, to assign enlisted Marines to serve as custodians under the supervision of the senior diplomatic officer at an embassy, legation, or consulate,” (DoS 1999). The MSGs presently number approximately 1,500 Marines stationed at 149 detachments, which are organized into nine regional commands. Table 1.1 depicts the regional headquarters location, area of responsibility (AOR), and number of detachments for each region.

The Marine Corps assumed the primary training responsibility of MSGs in 1954. Training currently takes place in two- to three-month periods at MSG School in Marine Corps Base (MCB) Quantico. MSG School processes five classes of 80–100 students annually. Thus, there are five MSG rotations every year, each corresponding to a graduating class. The rotating Marines can be placed into one of four experience levels: (1) MSG School to first detachment (1st Poster), (2) first to second detachment (2nd Poster), (3) second to third detachment (3rd Poster), or (4) rotating off MSG duty. MSGs rotating off of MSG duty can be rotating for three reasons: (1) they have successfully completed their service as an MSG and are rotating Off Program Completely (OPC), (2) they are physically unable to continue duty as an MSG and are being discharged from MSG duty for the Good of the Service (GOS), or (3) the MSG is being

Table 1.1: The region number, regional headquarters location, regional AOR, and number of detachments in each region.

<b>Region</b>	<b>Headquarters</b>	<b>Area of Responsibility</b>	<b>Detachments</b>
1	Frankfurt, Germany	Eastern Europe and Eurasia	17
2	Abu Dhabi, United Arab Emirates	Near East and South Asia	20
3	Bangkok, Thailand	East Asia and Pacific	18
4	Fort Lauderdale, Florida	Western Hemisphere - South	13
5	Frankfurt, Germany	Western Europe and Scandinavia	15
6	Frankfurt, Germany	East Africa	17
7	Frankfurt, Germany	North and West Africa	17
8	Frankfurt, Germany	Central Europe	18
9	Fort Lauderdale, Florida	Western Hemisphere - North	14

removed from MSG duty for legal reasons or Removed For Cause (RFC). For the purposes of the decision support tool, the term OPC encompasses OPC, GOS, and RFC conditions.

Detachments are categorized by a three-tier system based on desirability of the post. Tier designation is based on determinations made by the Department of State (DoS 1999). Tier 1 detachments are classified as those detachments that are in desirable locations, such as Paris, Rome, and Munich. Tier 3 detachments are considered less desirable locations, such as Port Au Prince, Rangoon, and Kiev. Tier 2 detachments are considered intermediate locations, such as Mexico City, Ankara, and Kuwait. One goal of the assignment process is to ensure that each MSG receives an equitable distribution of Tier 1, Tier 2, and Tier 3 assignments during his or her tour of duty.

MSG duty is designated as a three-year tour and comprises two or three detachments, depending on the rank of the MSG. A Detachment Commander (DetCmdr) leads each detachment. DetCmdrs are Marines that have achieved a rank of E-7 or E-8 and serve two detachments each lasting 18 months. Watchstanders are Marines who have achieved a rank of E-2 through E-6, which represents most MSGs. A typical tour for a watchstander is three detachments, each lasting 12 months.

### **1.2.2 Current Assignment Cycle**

The current MCESG assignment cycle comprises a lengthy and complex transfer of information between MCESG, the region commands, and the detachments. Due to the complexity of the process, the potential for human error is substantial.

An assignment cycle has three distinct periods: (1) the collection period, when MCEG collects information from the detachments; (2) the forecast period, when MCEG forecasts the placement of MSGs during the rotation; and (3) the rotation period, which involves the physical rotation of MSGs. Most of the assignment cycle is spent on the collection and forecast periods, which are the focus of this thesis.

The collection period involves a multistage process of organizing a series of Excel spreadsheets and MCEG-generated Marine administrative messages (MARADMINS). The MARADMINS are essentially MCEG’s formal requests for information from the region commands. The forecast period also involves a series of MCEG-generated MARADMINS, but these MARADMINS inform the region commands and detachments of the rotation details. Assignment cycles are referred to by X-YY notation in which X represents the assignment cycle number of the fiscal year (FY), which is represented by YY. Table 1.2 depicts an example of a typical assignment cycle as it corresponds to MSG School class 1-11, the first MSG School class to graduate in FY 2011.

Table 1.2: Class 1-11 assignment cycle periods, timeline, and messages.

Period	Date	MCEG to Regions/Detachments	Detachments to Regions/MCEG
Collection	8/16/2010	(1) Class 1-11 Scrub List (2) Post Requirements Request (3) Class 2-11 Designated Country Package Request	N/A
	8/23/2010	N/A	(1) Detachment Scrub List (2) Post Requirements
Forecast	8/30/2010	(1) Tentative Movement Message	N/A
	9/13/2010	N/A	(1) 2/3 Post Choices (2) Class 2-11 DC Packages
	9/20/2010	(1) A/ and DC Message	N/A
	10/11/2010	(1) 2/3 Poster Message	N/A
	11/01/2010	(1) Class 2-11 DC Board	N/A
	11/15/2010	(1) Class 1-11 Final Watchstander Message	N/A
Rotation	11/16/2010	Movement	

Class 1-11 Scrub List: This list contains information from the group of MSGs scheduled to rotate with the graduation of class 1-11 such as name, rank, social security number, and detachment preference. This list is completed at the region command level using information received directly from the embassy detachments.

Post Requirements Request: This request is distributed as a MARADMIN from MCEG to the region commands and then from the region commands to the detachments. MCEG requests

that each detachment identify its requirements, which are based on the forecasted empty billets for the upcoming rotation. Detachment requirements include information on rank and experience level.

Class 2-11 Designated Country (DC) Package Request: A DC is defined as a country in which MSGs are required to have a special security clearance. Table 1.3 lists the current DC detachments and detachment identification codes (DICs). The DC Package Request is distributed as a MARADMIN from MCESG to the region commands, and then the detachments. This message requests all DC-qualified MSGs scheduled to rotate in the 2-11 cycle to submit packages for DC post consideration.

Table 1.3: The current list of DC detachments and DICs (DoS, 1999).

<b>DIC</b>	<b>Region</b>	<b>City</b>	<b>Country</b>
A13	1	Moscow	Russia
B09	2	Jerusalem	Israel
B16	2	Tel Aviv	Israel
C02	3	Beijing	China
C03	3	Chengdu	China
C19	3	Shanghai	China
C20	3	Hanoi	Vietnam
D06	4	Caracas	Venezuela
I03	9	Havana	Cuba
I10	9	Port Au Prince	Haiti

Detachment Scrub List : This list is forwarded from each detachment to the region command. It contains information from the Marines scheduled to rotate in the upcoming rotation period. Once approved by the region command, the detachment scrub list is sent to MCESG. The detachment scrub list is similar to the Class 1-11 Scrub List except that it also contains information on the experience level of each rotating MSG.

Post Requirements: This list is sent from each detachment to the Region Command. The post requirements spreadsheet contains the billet requirements for every empty billet that needs to be filled during the upcoming rotation period. Once approved by the region command, it is forwarded to MCESG.

Tentative Movement Message: The Tentative Movement Message is released as a MARADMIN from MCESG to the region commands and then to the detachments. The purpose of this

message is twofold: (1) to serve as a way for MCESEG to confirm information already received from the detachments, specifically which Marines are scheduled to rotate and their information; and (2) to inform all rotating Marines about available billets and the requirements of each billet.

2/3 Post Choices: The 2/3 Post Choices is distributed as an Excel workbook from each region command to MCESEG assignment personnel. This document consists of assignment preferences for 2nd and 3rd Posters. The assignment preferences include three detachment preferences and two region preferences. The 2/3 Post Choices workbooks can only be created after the release of the Tentative Movement Message from MCESEG, since the Tentative Movement Message contains information on available billets.

A/ and DC Message: This message is released as a MARADMIN from MCESEG to the detachments. It assigns current DetCmdrs, Assistant Detachment Commanders (A/), and DC qualified Marines to posts for the current rotation period.

2/3 Poster Message: The 2/3 Poster Message is released as a MARADMIN from MCESEG and serves as the assignment message for all MSGs who are rotating to their second or third post. Region commands verify the information and, if needed, contact MCESEG to request changes prior to the final assignment message.

Class 2-11 DC Board: This message is released as a MARADMIN from MCESEG to the region commands and informs the detachments that a DC Board for Class 2-11 is being convened. DC-eligible MSGs are placed in a DC post during the class 2-11 rotation period.

Class 1-11 Final Watchstander Message: This message is released as a MARADMIN from MCESEG approximately one week prior to the graduation date for the current class. It consists of the 2/3 Poster Message and the assignment of all 1st Posters. If there are more 1st Posters than available billets from the 2/3 Poster message, then Marines moving with the next assignment cycle (i.e., class 2-11) will be replaced early.

## **1.3 Related Work**

The literature review focuses on characteristics of successful optimization models and techniques commonly used when developing personnel assignment optimization models. Integration of such models with information management systems is also examined.

Extensive research has examined personnel assignment with network flow models. Bausch

et al. (1991) address assignment optimization with respect to the immediate mobilization of Marine Corps officers. The authors designed and built the Manpower Assignment Recommendation System (MARS). MARS is a decision support tool based on a network flow model that works in conjunction with Marine Corps databases to complete a wartime mobilization involving 40,000 officers and 27,000 billets (Bausch et al. 1991). Their model combines three objectives:

1. Maximize the number of billets filled with qualified officers.
2. Maximize the fit of the officer to the billet. Their model strives to obtain a perfect officer-billet fit and avoids sending over- or under-qualified officers to any billet. MSGAT also seeks to maximize the fit of each Marine-billet assignment using similar fit criteria, such as rank and gender.
3. Minimize the amount of movement when filling the billets. That is, their model aims to keep as many officers in the same unit that they were assigned to prior to mobilization.

Two files are critical to their work: the wartime officer slate file (WOSF) and the wartime authorized strength report (WASR). The WOSF contains information on Marines, much like the Scrub List and Post Choices worksheets, while the WASR describes billets and their requirements, much like the Post Requirements worksheet. A conceptual network model of the Marine Corps mobilization problem depicts each officer as a supply node and each billet as a demand node (Bausch et al. 1991). MARS employs several important refinements to the conceptual model since a literal implementation of the conceptual model is computationally impractical (Bausch et al. 1991). Prior to their work, the existing Marine Corps system took up to four days to complete a mobilization and produced substandard results. Their network flow model produces results quicker and significantly better with respect to all MOEs.

The United States Army consists of over 1.5 million personnel. The Army frequently adjusts the stationing of its force structure as weapons systems, missions, and operations change over time. Dell, Ewing, and Tarantino (2008) use an integer linear program, Optimally Stationing Army Forces (OSAF), to provide optimal Army stationing for a given set of installations. The OSAF model prescribes optimal Army stationing by using the existing starting locations, set of installations, and unit requirements to minimize cost associated with Base Realignment and Closure (BRAC) decisions, while maximizing military value (Dell, Ewing, and Tarantino 2008). Each

stationing plan satisfies a myriad of unit requirements, such as building and land availability. Similarly, each assignment solution generated by MSGAT satisfies various MSG and billet requirements identified by MCESG and the region commands. OSAF has assisted with BRAC decisions since 2005 and has successfully provided the Army with reliable stationing analysis for several years. Although this model is a stationing analysis tool, OSAF is analogous to other types of analysis (Dell, Ewing, and Tarantino 2008).

The primary objective of the Marine Corps Manpower System (MCMS) is to maximize the Marine Corps' operational readiness through the assignment of officers to billets. While striving to fulfill billet requirements, MCMS simultaneously develops the professional skills that each officer must possess to be assigned to billets as their careers progress (Baumgarten 2000). Thus, career paths must be designed to reflect the balance of fulfilling billet requirements and developing professional skills. Baumgarten (2000) presents a mixed integer program, the Officer Career Path Selection (OCPS) model, that assigns officers to acceptable career paths in order to meet billet requirements while satisfying professional skill development. OCPS assists in determining the number of officers to assign to various Military Occupational Specialties (MOSS) each year.

Tivnan (1998) presents a network model, Enlisted Assignment Model-Global (EAM-GLOBAL), that serves to optimize the assignment of enlisted Marines to billets. EAM-GLOBAL seeks to assign the best Marine-billet fit while balancing staffing shortages, allowing grade and MOS substitutions, and minimizing the monetary cost associated with moving Marines (Tivnan 1998). Four assignment MOEs are used to determine how well EAM-GLOBAL's assignments satisfy United States Marine Corps (USMC) staffing goals:

1. Fill percentage of billets.
2. Number of transcontinental United States transfers.
3. Percentage of filled billets with perfect fit. The authors define perfect fit as exact grade and MOS match between Marine and billet.
4. Number of Marines available but not assigned.

EAM-GLOBAL verifies that the current inventory of enlisted Marines can achieve over 99% of the staffing goals.

The Basic School (TBS) is the first school assignment for all Marine officers. While assigned to TBS, unrestricted ground officers are assigned a particular MOS (Goldschmidt and Boersma 2003). The assignment of the MOS is based on the officer's lineal standing within their cohort at TBS and the demands of the Marine Corps. Lineal standing is a ranking based on academic and leadership grades attained throughout TBS. To ensure quality distribution of officers, each cohort within TBS is divided into thirds based on lineal standing (Goldschmidt and Boersma 2003). The MOS vacancies are divided into thirds as well. Goldschmidt and Boersma (2003) develop an information management system, MyMOS, for use by TBS personnel that assists in the collection of information and the assignment of MOSs to newly commissioned officers. Each MOS assignment model is an integer linear program that optimally assigns an MOS to an officer using the officer's lineal standing, MOS preferences, third, and MOS availability. In addition to the numerical improvements realized by linear programming, Goldschmidt and Boersma (2003) achieve substantial cost savings by reducing the manpower involvement in the prior assignment cycle process.

Loerch et al. (1996) develop an integer program to determine efficient stationing solutions for the United States Army in Europe. The authors design their model to achieve the desired objectives of minimizing monetary costs, maintaining unit integrity, and fulfilling unit support requirements (Loerch et al. 1996). Model results were provided as a basis for developing stationing plans throughout Europe.

Brown, Dell, and Wood (1997) discuss the importance of incorporating persistence in optimization-based decision support tools. Persistence is required because optimization has the potential to amplify small input changes into drastically different solutions (Brown, Dell, and Wood 1997). This is especially troublesome in a cyclic process such as the MCESG assignment process. In this process, MCESG produces an assignment, the assignment is published, revised MSG or billet data becomes available, MCESG produces a revised assignment, and the revised assignment is published. New assignments that retain features of prior assignments are more desirable to MCESG, as this limits the amount of disruption to MSGs' planned rotations. Thus, MSGAT contains a user-defined parameter that represents the maximum number of changes between any two assignments.

## **1.4 Contributions**

MSGAT is an Excel-based decision support tool that utilizes a system of workbooks to guide MCESG through the assignment cycle process. MSGAT accomplishes the following:



- Streamlines the data collection process by standardizing the format of MSG and billet information and utilizing a user interface that breaks each assignment cycle up into 8 distinct phases. These phases are described in Section 1.4.2;
- Formulates a robust and flexible network flow model that provides MCEG personnel with a mathematically optimal assignment;
- Balances MSG experience level across detachments;
- Enables the creation of several assignment solutions while minimizing the number of changes between assignments; and
- Enables comparison of assignments with respect to MCEG-identified MOEs.

### **1.4.1 The Goal Set**

Development of MSGAT begins with research of current methods at MCEG to determine inputs, constraints, and variables for the network flow model. MCEG manual assignments attempt to satisfy the MOEs identified by directives set forth in the MCEG Group Bulletin 5000 (dated June 2010) (Fairfield 2010).

1. Fill all designated country (DC) billets with qualified Marines;
2. All detachments requiring an A/ are filled with personnel qualified to serve as an A/;
3. Every detachment will receive roughly the same number of 1st posters, 2nd posters, and 3rd posters as well as a balanced grade structure;
4. Each MSG will receive an equitable assignment to detachments of varying tiers;
5. The preferences of the MSG are considered once the aforementioned priorities have been satisfied.

Additionally, MCEG attempts to satisfy a number of other MOEs not identified in the MCEG Group Bulletin. For example, MCEG attempts to avoid sending female MSGs to detachments that are not configured for females, and MCEG attempts to fill all billets in small detachments. These small detachments, denoted as 1/5 Posts, consist of one DetCmdr and five watchstanders. Table 1.4 contains MCEG's complete goal set.

Table 1.4: The set of goals that MSGAT satisfies when making MSG-billet assignments.

Attribute	Goal
Post Restrictions	MSGs will not be assigned to embassies in which they are restricted from serving.
Repeat Region	MSGs will not be assigned to the same region more than once.
Gender	Female MSGs will not be assigned to embassies that are not configured for females.
DC	Only DC-qualified MSGs are assigned to DC embassies.
A/	Only MSGs qualified to serve as an A/ are assigned to billets requesting an A/.
Experience Level	MSG experience level is balanced across all detachments.
Rank	MSG rank is balanced across all detachments.
Tier	MSGs will not be assigned to the same tier more than once.
Preferences	MSGs will be assigned to one of three detachment preferences or one of two region preferences.
1/5 Posts	All billets in 1/5 Posts have priority over billets in more populous embassies.
Staff Sergeant (SSgt) Select	Billets needing SSgt-selects receive MSGs selected for the rank of SSgt.

### 1.4.2 Streamlining Information Flow

MSGAT streamlines the flow of information between detachments, region commands, and MCESG. Figure 1.1 illustrates the flow of information when collecting and disseminating information during an assignment cycle.

The development of a more efficient data collection process accomplishes the following:

- Ensures that MCESG receives all necessary MSG and billet information during creation of the Scrub List and Post Requirements documents;
- Informs MSGs of available billets and associated requirements; and
- Provides region commands complete oversight of MSG and billet information.

The decision support tool streamlines the assignment-cycle process in two distinct ways. First, MSG and billet data format is standardized. The current process does not constrain the format in which MSG and billet data is transmitted between MCESG, regions, and detachments. This

results in assignments personnel being unable to perform basic functions on groups of data, such as sorting and counting. The lack of a standardized format also causes confusion at various levels of command. Chapter 3 discusses how MSGAT uses Excel userforms and Visual Basic for Applications (VBA) to force proper data formatting.

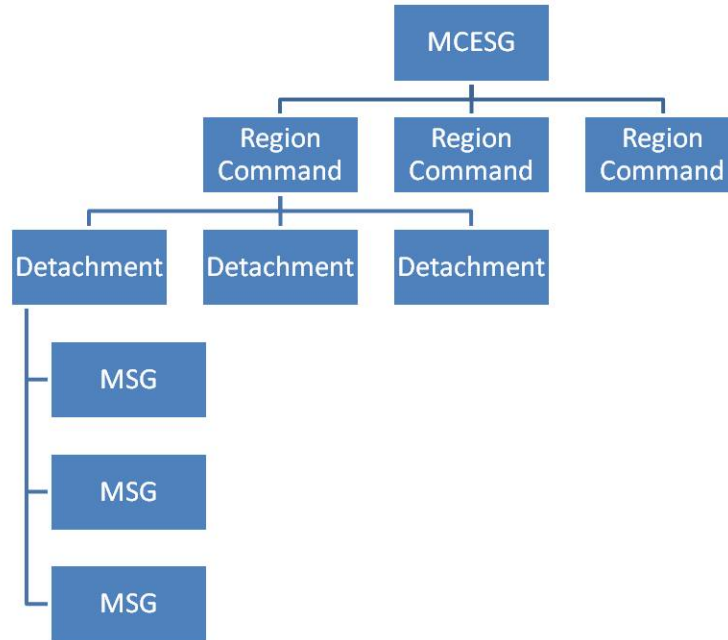


Figure 1.1: The flow of information when building the database of inputs. Requests for information are submitted to the region commands from MCESG headquarters. Region commands compile information from the detachments and return to MCESG assignment personnel.

Second, MSGAT streamlines the assignment-cycle process by decomposing it from the three broadly defined periods into eight concisely defined phases.

1. Cycle Initiation: MCESG personnel update detachment information such as tier level or number of watchstanders allowed. Once the detachment information is updated, MCESG initiates the assignment cycle. Initiation involves creating the Excel workbooks and files necessary for the optimization algorithm.
2. Scrub List and Post Requirements: This phase consists of initial information collection on rotating MSGs and vacating billets from region commands.
3. Tentative: MCESG uses the Scrub List and Post Requirement documents to create the Tentative Movement Message. The Tentative Movement Message is distributed to the region commands to inform rotating MSGs of available billets.

4. Post Choices: Region commands use the Tentative Movement Message to build the Post Choices document. The Post Choices document consists of Scrub List information and MSG preferences.
5. 2/3 Poster Message: Assignment optimization occurs during the creation of the 2/3 Poster Message. This message contains the assignment of all 2nd and 3rd Posters. The 2/3 Poster Message is distributed to the region commands.
6. 1st Poster Information: MCESEG collects information from all MSGs at MSG school and scheduled to rotate in the current assignment cycle as 1st Posters.
7. Final Message: Assignment optimization occurs again during the creation of the Final Message. MCESEG uses the 1st Poster information and the 2/3 Poster Message to create the Final Message. The Final Message contains the assignment of all MSGs and is distributed to the region commands.
8. Message Changes: Optmization also occurs when MCESEG makes any necessary changes to either the 2/3 Poster Message or the Final Message. The message changes are distributed to the region commands.

### **1.4.3 User Interface**

Users interact with MSGAT via a series of Excel workbooks. These workbooks originate at MCESEG and are passed down to the region commands. The administrative personnel at each region command retrieve information from the detachments themselves, compile this information, and return the completed workbook to MCESEG in accordance with the aforementioned phases. Assignment personnel at MCESEG then compile all MSG information and redistribute, as necessary, to the region commands for verification and updating. This process is described in detail in Chapter 3.

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# CHAPTER 2:

## MODEL DEVELOPMENT

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### 2.1 Introduction

MSGAT implements a multicommodity network flow model to optimally assign MSGs to billets. This model, denoted as the Balance Model and described in formulation BALMOD, is derived from the classical assignment model. Formulation BALMOD is capable of optimizing assignments based on characteristics unique to individual MSGs and billets, as well as detachment-level objectives. Formulation BALMOD is described in Section 2.2. The Assignment Modification formulation ASMOD is an extension of BALMOD that is capable of generating similar assignments using varying sets of input data. This formulation is described in Section 2.3.

### 2.2 Model BALMOD

The goals of MSGAT are to optimally assign MSGs to billets and to balance MSG experience levels across all detachments. MSGAT accomplishes these goals by solving a multicommodity network flow problem in which MSG experience levels serve as commodities. A schematic diagram of the network solved by MSGAT is shown in Figure 2.1. This multicommodity network flow problem is solved using formulation BALMOD, which is given in Section 2.2.1.

Model BALMOD matches MSGs to billets based on a number of attributes. These attributes are described in detail in Section 2.2.2 and Appendix A. BALMOD allows the user to exercise a degree of control over the assignment process by setting weights that emphasize or deemphasize particular attributes. Additionally, BALMOD allows the user to force or forbid assignments of MSGs to detachments through the use of a force/forbid matrix. This matrix is described in more detail in Section 2.2.1.

For simplicity, the formulation described in this thesis assumes that the number of MSGs rotating is equal to the number of billets available. In reality, the number of rotating MSGs and available billets are not necessarily equal in every assignment cycle. Thus, MSGAT executes a pre-processing step to handle unequal numbers of MSGs and billets.

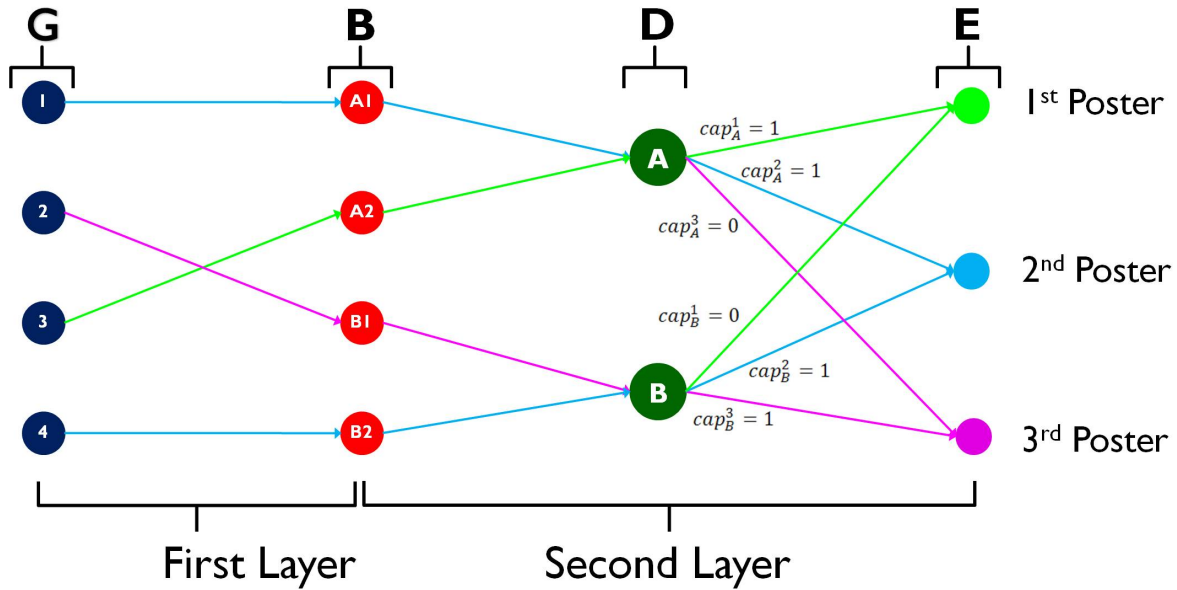


Figure 2.1: Formulation BALMOD is a two-layer, multicommodity network consisting of four sets of nodes,  $G$ ,  $B$ ,  $D$ , and  $E$ , as well as three edge sets. The first layer minimizes MSG-billet cost with respect to attributes unique to MSGs and billets. The second layer balances MSG experience across detachments.

## 2.2.1 BALMOD Formulation: NPS Format

### Indices and Sets:

$g \in G$	MSG.
$b \in B$	Billet.
$k \in K$	MSG or billet attribute.
$det \in D$	Detachment.
$e \in \{1, 2, 3\}$	MSG experience level.
$c \in \{1, 2, 3\}$	Flow commodity.
$G_e \subseteq G$	Set of MSGs with experience level $e$ .
$B_{det} \subseteq B$	Set of billets located in detachment $det$ .

### Input Data:

$det(b)$	Parent detachment of billet $b$ .
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$v_{g,b}^k$	Penalty incurred by MSG $g$ and billet $b$ for attribute $k$ .
$w_k$	Weight given to attribute $k$ .
$w_{bal}$	Weight given to the experience balance attribute.
$pen_e^c$	Penalty for assigning an MSG with experience $c$ to a slot requiring experience level $e$ .
$f_{g,b}$	Force/forbid matrix.
$E_g^c$	= 1 if guard $g$ has experience level $c$ , 0 otherwise.

### Calculated Data:

$cost_{g,b} = \sum_k w_k v_{g,b}^k$	Cost of assigning MSG $g$ to billet $b$ , excluding the experience penalty.
$dem_{det}^e$	Target level for experience $e$ at detachment $det$ .

### Decision Variables:

$ASSIGN_{g,b}^c$	Decision to assign MSG $g$ with experience level $c$ to billet $b$ . [binary]
$BILLET_{b,det(b)}^c$	Decision to assign billet $b$ in detachment $det(b)$ to a guard with experience level $c$ . [binary]
$EXSLOT_{det,e}^c$	Number of MSGs with experience level $c$ assigned to detachment $det$ and assigned to slots requiring experience $e$ .

### Formulation: BALMOD

$$\min_{\substack{ASSIGN \\ BILLET \\ EXSLOT}} \sum_{g,b} \left( cost_{g,b} \cdot \sum_c ASSIGN_{g,b}^c \right) + w_{bal} \cdot \sum_{det} \sum_{c,e} pen_e^c \cdot \frac{EXSLOT_{det,e}^c}{\max_{c,e}(pen_e^c) \cdot |B_{det}|}$$

$$s.t. \sum_b ASSIGN_{g,b}^c = E_g^c \quad \forall g, c \quad (2.3.0)$$

$$\sum_{g,c} ASSIGN_{g,b}^c = 1 \quad \forall b \quad (2.3.1)$$

$$\sum_g ASSIGN_{g,b}^c = BILLET_{b,det(b)}^c \quad \forall b, c \quad (2.3.2)$$



$$\sum_{b \in B_{det}} BILLET_{b,det}^c = \sum_e EXSLOT_{det,e}^c \quad \forall det, c \quad (2.3.3)$$

$$\sum_c EXSLOT_{det,e}^c \leq dem_{det}^e \quad \forall det, e \quad (2.3.4)$$

$$\sum_c ASSIGN_{g,b}^c \leq f_{g,b} \quad \forall g, b \quad (2.3.5)$$

$$ASSIGN_{g,b}^c \in \{0, 1\} \quad \forall g, b, c \quad (2.3.6)$$

$$BILLET_{b,det}^c \in \{0, 1\} \quad \forall b, det, c \quad (2.3.7)$$

$$EXSLOT_{det,e}^c \geq 0 \quad \forall det, e, c \quad (2.3.8)$$

As Figure 2.1 shows, BALMOD solves a two-layer multicommodity network flow problem in which the commodities are MSG experience levels. This network contains four sets of nodes; a set representing guards,  $G$ ; a set representing billets,  $B$ ; a set representing detachments,  $D$ ; and a set representing experience slots,  $E$ . The first layer of this network including the nodes in  $G$  and  $B$  and the arcs connecting them, behaves as a classical assignment model, assigning MSGs to billets based on attributes unique to MSGs and billets. The second layer of the network ensures that MSG experience is balanced across detachments. The arcs connecting nodes in  $D$  to nodes in  $E$  carry penalties based on the commodity of flow (MSG experience level) and the experience level of the destination node. These arcs have capacities that indicate the number of slots of each experience level that are needed at each detachment. Further motivation for the use of a two-layer network over a classical assignment model is given in Section 2.2.3.

### BALMOD Objective Function

The objective function in model BALMOD contains two terms. The first term records costs associated with attributes unique to MSGs and billets. The parameter  $cost_{g,b}$  is a goodness-of-fit measure that is calculated using parameters  $w^k$  and  $v_{g,b}^k$ .  $w^k$  is a weight parameter that is tunable by the user; it is designed to allow the user to emphasize or deemphasize particular attributes in the cost calculation. Weights  $w^k$  take on values between 0 and 100.  $v_{g,b}^k$  is the penalty incurred by MSG  $g$  and billet  $b$  for attribute  $k$ . Penalties  $v_{g,b}^k$  take on values between 0 and 1. A full description of penalties  $v_{g,b}^k$  can be found in Appendix A.

The second term in the objective function records penalties related to the balance of experience levels across detachments. Each arc connecting a node in  $D$  to a node in  $E$  carries a cost that depends on the level of mismatch between MSG experience level (flow commodity) and

experience level represented by the target node in  $E$ . Note that a normalization factor is included in the objective function term relating to the balance penalty. This is done in order to ensure that the resulting balance penalty is between 0 and 1, as the penalties for the other attributes are.

### BALMOD Constraints

Constraint 2.3.0 ensures that each guard  $g$  with experience  $c$  is assigned to one billet  $b$ . Constraint 2.3.1 ensures that each billet  $b$  is assigned one MSG  $g$ . Constraint 2.3.2 ensures flow conservation at each billet node in Figure 2.2. Constraint 2.3.3 ensures flow conservation at each detachment node in Figure 2.2. Constraint 2.3.4 ensures correct calculation of the experience balance penalty, given detachment experience demands. Constraint 2.3.5 enforces conditions expressed by the force/forbid matrix. Constraint 2.3.6 indicates that the assignment of MSG  $g$  with experience  $c$  to billet  $b$  can be either 0 or 1. Constraint 2.3.7 indicates that the assignment of experience  $c$  to billet  $b$  in detachment  $det$  can be either 0 or 1. Constraint 2.3.8 indicates that the assignment of experience  $c$  to an experience slot  $e$  in detachment  $det$  is greater than or equal to 0.

### Detachment Experience Demands

Detachment experience demands  $dem_e^{det}$  indicate the number of MSGs with each experience level  $e$  required at each detachment  $det$  in order to balance experience levels across detachments. This section describes the calculation of  $dem_e^{det}$ .

Denote the overall fraction of MSGs with experience level  $e$  by  $frac_e$ .  $frac_e$  includes both rotating and non-rotating MSGs. Denote the number of MSGs with experience level  $e$  that are *not* rotating out of detachment  $det$  by  $S_e^{det}$ . Finally, recall that the number of open billets at detachment  $det$  is given by  $|B(det)|$ . MSGAT uses the following simple calculation to set the detachment experience demands  $dem_e^{det}$ :

$$\begin{aligned} dem_e^{det} &= \max(0, \lfloor frac_e |B(det)| \rfloor - S_e^{det}) \quad \forall e = 2, 3 \\ dem_1^{det} &= |B(det)| - dem_2^{det} - dem_3^{det} \end{aligned}$$

This demand calculation attempts to evenly distribute experience levels over all detachments. Future improvements to MSGAT may include a more sophisticated calculation of  $dem_e^{det}$ . Each

unit of MSG experience demand at a detachment shall henceforth be referred to as a *slot*.

### **The Force/Forbid Matrix $f$**

The force/forbid matrix  $f_{g,b}$  allows the user to either force or forbid the assignment of an MSG to a specific detachment.

1. To force an assignment between MSG  $g$  and detachment  $det$ :

(a)  $f_{g,b} = 1 \forall b \in B_{det}$

(b)  $f_{g,b} = 0 \forall b \notin B_{det}$

2. To forbid an assignment between MSG  $g_1$  and detachment  $det$ :

(a)  $f_{g,b} = 0 \forall b \in B_{det}$

The force/forbid matrix also captures any necessary post restrictions other than those entered manually by the user.

Allowing the forcing or forbidding of MSGs-detachments assignments enables the user to make the problem infeasible. MSGAT executes infeasibility corrections prior to implementing the optimization algorithm if the user performs one of the following actions.

- Forces more MSGs than available billets at a detachment.
- Forces and forbids an MSG to the same detachment.

In addition to these feasibility checks, a post-processing step also verifies solution quality and notifies the user of any potential problem with MSGAT's output.

### **2.2.2 Attributes**

MSGAT considers several attributes when determining goodness of fit between an MSG and a billet. Attributes are characteristics of MSGs, billets, or detachments. Table 2.2 contains the attributes and whether goal satisfaction is a characteristic of the detachment or MSG/billet.

Input data for BALMOD are collected at the region level. In addition to MSG and billet data, model BALMOD also requires the number of first, second, and third posters currently serving at

Table 2.2: The set of goals that MSGAT satisfies when making MSG-billet assignments.

Entity	Attribute	Goal
Detachment	Experience Level	MSG experience level is balanced across all detachments.
	Rank	MSG rank is balanced across all detachments.
MSG/billet	Post Restrictions	MSGs will not be assigned to embassies in which they are restricted from serving.
	Repeat Region	MSGs will not be assigned to the same region more than once.
	Gender	Female MSGs will not be assigned to embassies that are not configured for females.
	DC	Only DC-qualified MSGs are assigned to DC embassies.
	A/	Only MSGs qualified to serve as an A/ are assigned to billets requesting an A/.
	Tier	MSGs will not be assigned to the same tier more than once.
	Preferences	MSGs will be assigned to one of three detachment preferences or one of two region preferences.
	1/5 Posts	All billets in 1/5 Posts have priority over billets in more populous embassies.
SSgt Select	Billets needing SSgt selects receive MSGs selected for the rank of SSgt.	

each detachment, not including those MSGs rotating in the current cycle. Additionally, MSGAT collects some data that are not used in model BALMOD, but that must be recorded for purposes of record keeping. One example of such data is the first and last name of each rotating MSG. The data collected by MSGAT are summarized below.

### MSG Data

Input data from the Marines can be separated into personal data and MSG related data. Personal data includes all personally identifiable information, unique to every MSG. MSG related data is information that the Marine has acquired while on MSG duty.

#### 1. Personal data:

- (a) Name — last name, first name and middle initial of MSG.
- (b) Rank — MSG rank.

- (c) Rotation Tour Date — the date that the MSG is scheduled to rotate off of MSG duty.
- (d) Date of Rank — the date that the MSG was promoted to their current rank.
- (e) Date Current Tour Began — the date that the MSG began MSG duty. This date coincides with the date that the MSG began MSG School.
- (f) Gender

2. MSG related data:

- (a) Experience — the experience level of the Marine. MSGs are classified as 1st, 2nd, or 3rd Posters.
- (b) A/-qualified — designation of this MSG as an A/. Although MCESEG will continue to manually assign A/ positions in the formal A/ and DC Message, there are cases in every assignment cycle in which not all billets requiring an A/-qualified MSG are identified initially.
- (c) Prior duty stations — the DIC and tier of prior duty stations.
- (d) Post restrictions — regions that the Marine is prohibited from being assigned. Restricted posts are posts that the MSG has already served or posts that the MSG is not qualified to serve. For example, an MSG with family members in Australia would not be able to serve in any post in Region 3 – East Asia and Pacific because detachment 0C04 is located in Canberra, Australia.
- (e) Preferences — MSG's preferred duty stations.
  - i. Three detachment choices.
  - ii. Two region choices.

**Billet Data**

Input data from billets can be separated into general data and requirements based data.

1. General data:

- (a) Marine Command Code (MCC) — a four-digit, alphanumeric string that is used by Headquarters Marine Corps (HQMC) to identify units. This is also called the DIC.
- (b) Current MSG — the MSG currently assigned to the billet.
- (c) Tier — tier level of the parent detachment.

- (d) DC — designator that indicates whether this billet is located in an embassy within a DC.
- (e) 1/5 Post — designator that indicates whether this billet is located in a 1/5 post. A 1/5 post is an embassy with one DetCmdr and five watchstanders on the Table of Organization (T/O). The T/O represents the number of personnel that HQMC has authorized at a unit. These embassies have the fewest number of MSGs assigned to them.

2. Requirements based data:

- (a) Requested rank — rank requested at the billet.
- (b) SSgt select — designator that indicates if the billet is requesting an MSG selected for the rank of SSgt.
- (c) Requested experience — MSG experience level requested at the billet.
- (d) A/ — indicator that designates whether this billet is requesting an A/-qualified MSG.
- (e) Gender — indicator that designates the gender requested at the billet.

**Detachment Data**

Input data from the detachments is separated into general data and experience-based data.

1. General data:

- (a) Billets — the number of billets that the detachment is requesting.
- (b) Authorized Watchstanders — the number of watchstanders that are authorized on the detachment T/O.

2. Experience based data:

- (a) 1st Posters — the number of 1st Posters currently serving at the detachment, not including any rotating MSG.
- (b) 2nd Posters — the number of 2nd Posters currently serving at the detachment, not including any rotating MSG.
- (c) 3rd Posters — the number of 3rd Posters currently serving at the detachment, not including any rotating MSG.

### 2.2.3 Limitations of the Classical Assignment Model

In contrast to the classical assignment model, model BALMOD is a integer linear program. The addition of integer constraints is necessary because, as a multicommodity network flow problem, the LP relaxation of BALMOD is not guaranteed to have an integer optimal solution (although, in practice, it nearly always does). The addition of integer constraints can be expected to greatly increase computation time on some problem instances. Thus, some justification of the use of model BALMOD over a classical assignment model is desirable.

To see the limitations of the classical assignment model, note that two of the goals in Table 2.2 involve balancing an attribute across detachments. Namely, both MSG ranks and MSG experience levels must be balanced across detachments. The following example illustrates the limitations of the classical assignment model in balancing both rank and experience level across two detachments using only billet-level attributes.

#### Example

Consider the scenario illustrated in Tables 2.3 and 2.4. In this case, MSG 1 is an E4 2nd Poster, MSG 2 is an E4 3rd Poster, MSG 3 is an E5 1st Poster, and MSG 4 is an E6 2nd Poster. Detachment A has two billets; one requesting an E4 and the other requesting an E5. Detachment B has two billets; one requesting an E4 and the other requesting an E6. Detachment A needs one 1st Poster and one 2nd Poster to balance MSG experience level. Detachment B needs one 2nd Poster and one 3rd Poster. Experience requirements and rank requests are linked to the billets instead of the detachments to illustrate the limitations of the classical assignment model.

Table 2.3: MSG attributes.

MSG	Rank	Experience
1	E4	2nd Poster
2	E4	3rd Poster
3	E5	1st Poster
4	E6	2nd Poster

Suppose that  $w_{Rank} = w_{Exp} = 1$ . Tables 2.5 and 2.6 contain the experience and rank penalties, respectively. Table 2.7 represents the cost table for the MSG and billet data in this example.

Figure 2.2 illustrates two possible solutions. The solution on the left is the optimal solution achieved by the classical assignment model given the data in Tables 2.3, 2.4, and 2.7. While both solutions satisfy the rank requirement at each billet, only the solution on the right satisfies

Table 2.4: The detachment and billet information for the example. Rank requests and experience requirements are linked to the billets to illustrate the limitations of the classical assignment model.

Detachment	Billet	Requested Rank	Requested Experience
A	A1	E4	1st Poster
	A2	E5	2nd Poster
B	B1	E4	2nd Poster
	B2	E6	3rd Poster

Table 2.5: Definition of the penalty  $v_{g,b}^{Exp}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the billet does not receive a requested experience level.

Billet Request	MSG Experience	$v_{g,b}^{Exp}$
1st Poster	1st Poster	0
	2nd Poster	0.5
	3rd Poster	1
2nd Poster	1st Poster	0.5
	2nd Poster	0
	3rd Poster	0.7
3rd Poster	1st Poster	1
	2nd Poster	0.5
	3rd Poster	0
Any	1st Poster	0
	2nd Poster	0
	3rd Poster	0

the rank requirement and balances experience. The optimal solution to the classical assignment model won't necessarily balance MSG experience level if rank and experience level are tied to individual billets. Thus, the classical assignment model is able to balance either rank or experience at the billet level, but not both.

As demonstrated in the previous example, detachments cannot simultaneously balance two attributes at the billet level. However, because attributes other than the required rank and experience level are constant throughout a detachment or are linked to rank, detachments *can* balance the rank attribute at the billet level. Thus, balance of rank is ensured via rank requests at the billet level, while balance of experience level is accomplished via the addition of a second layer to the classical assignment model network.



Table 2.6: Definition of the penalty  $v_{g,b}^{Rank}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the billet does not receive a requested MSG rank.

Billet Request	MSG Rank	$v_{g,b}^{Rank}$
E3	E3	0
	E4	0.3
	E5	0.6
	E6	1
E4	E3	0.3
	E4	0
	E5	0.3
	E6	0.6
E5	E3	0.7
	E4	0.3
	E5	0
	E6	0.3
E6	E3	1
	E4	0.6
	E5	0.3
	E6	0
Any	E3	0
	E4	0
	E5	0
	E6	0

Table 2.7: The cost table for the MSG and billet data from Tables 2.3 and 2.4, respectively. The highlighted costs illustrate the MSG-billet assignments.

		Billets			
		A1	A2	B1	B2
MSGs	1	0.5	0.3	0	1.1
	2	1	1	0.7	0.6
	3	0.3	0.5	0.8	1.3
	4	1.1	0.3	0.6	0.5

## 2.2.4 Single Commodity Formulation

For ease of implementation in MSGAT, the multicommodity formulation BALMOD is reformulated as a single commodity network flow problem with side constraints. This reformulation, called SINGCOM, is described in Appendix B. The solver utilized by MSGAT is explained in Section 3.3.5.

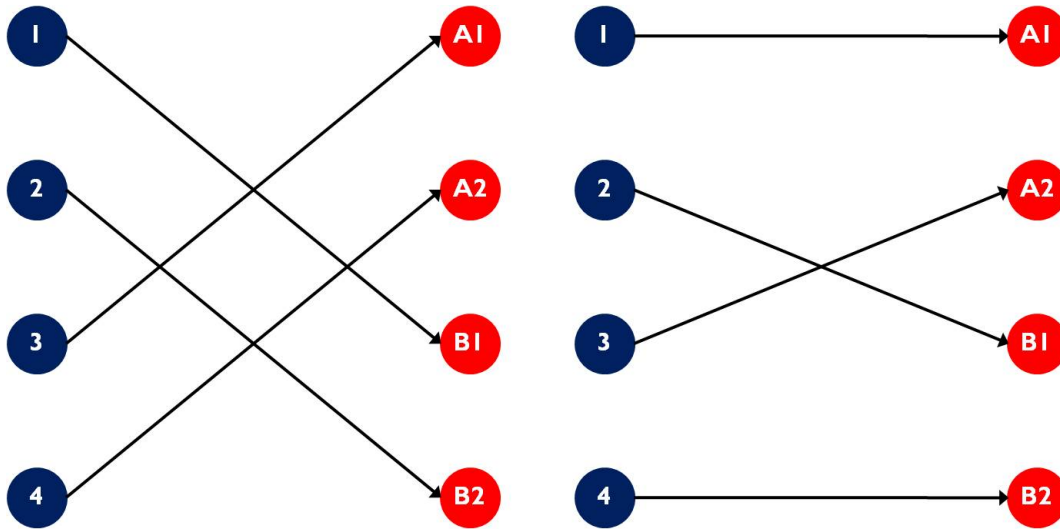


Figure 2.2: Two possible solutions for the given MSG and billet data. The solution on the left is calculated using the classical assignment model. The solution on the right satisfies the rank requirements at each detachment and balances out MSG experience level.

## 2.3 Assignment Modification

MCESG assignment personnel need to have the ability to make small changes to existing assignments. It is not uncommon for 2/3 Poster Messages and Final Messages to undergo several modifications throughout an assignment cycle. These modifications are based on changes in input data. Some examples of changes in input data are variation in attribute weights or alterations in MSG and billet information. Normally, modifications involve the alteration of several MSG-billet assignments. It is important that the changes in input data do not result in many changes in the new assignment relative to an existing assignment. The Assignment Modification formulation ASMOD described in this section introduces a new input parameter,  $d_{max}$ , that allows the user to select the maximum number of changes that can be made between assignments. This new parameter enables MCESG to define the degree of persistence between assignments and is implemented via the assignment modification formulation ASMOD.

### 2.3.1 Formulation ASMOD

Formulation ASMOD has the same functionality of formulation BALMOD and is also capable of generating similar assignments using varying sets of input data.

#### Indices and Sets:

$g \in G$	MSG.
$b \in B$	Billet.
$k \in K$	MSG or billet attribute.
$det \in D$	Detachment.
$e \in \{1, 2, 3\}$	MSG experience level.
$c \in \{1, 2, 3\}$	Flow commodity.
$G_e \subseteq G$	Set of MSGs with experience level $e$ .
$B_{det} \subseteq B$	Set of billets located in detachment $det$ .

### Input Data:

$det(b)$	Parent detachment of billet $b$ .
$v_{g,b}^k$	Penalty for MSG $g$ , billet $b$ , attribute $k$ .
$w_k$	Weight given to attribute $k$ .
$w_{bal}$	Weight given to the experience balance attribute.
$pen_e^c$	Penalty of assigning a guard with experience $c$ to a slot requiring experience level $e$ .
$f_{g,b}$	Force/forbid matrix.
$E_g^c$	= 1 if guard $g$ has experience level $c$ , 0 otherwise.
$d_{max}$	Maximum number of changes between an old assignment and a new assignment.
$x_{g,b}^{old}$	MSG/billet assignment in the assignment being modified.

### Calculated Data:

$cost_{g,b} = \sum_k w_k v_{g,b}^k$	Cost of assigning MSG $g$ to billet $b$ , excluding the experience penalty.
$dem_{det}^e$	Target level for experience $e$ at detachment $det$ .

### Decision Variables:

$ASSIGN_{g,b}^c$	Decision to assign MSG $g$ with experience $c$ to billet $b$ .
------------------	--

$BILLET_{b,det(b)}^c$	Decision to assign billet $b$ in detachment $det(b)$ to an MSG with experience level $c$ .
$EXSLOT_{det,e}^c$	Number of MSGs with experience level $c$ assigned to detachment $det$ and assigned to slots requiring experience $e$ .
$DIFF_{g,b}$	Indicator variable for recording changes between the new assignment and the old assignment.

### Formulation: ASMOD

$$\min_{\substack{ASSIGN \\ BILLET \\ EXSLOT \\ DIFF}} \sum_{g,b} \left( cost_{g,b} \cdot \sum_c ASSIGN_{g,b}^c \right) + w_{bal} \cdot \sum_{det} \sum_{c,e} pen_e^c \cdot \frac{EXSLOT_{det,e}^c}{\max_{c,e}(pen_e^c) \cdot |B_{det}|}$$

$$s.t. \sum_b ASSIGN_{g,b}^c = E_g^c \quad \forall g, c \quad (2.4.0)$$

$$\sum_{g,c} ASSIGN_{g,b}^c = 1 \quad \forall b \quad (2.4.1)$$

$$\sum_g ASSIGN_{g,b}^c = BILLET_{b,det(b)}^c \quad \forall b, c \quad (2.4.2)$$

$$\sum_{b \in B_{det}} BILLET_{b,det}^c = \sum_e EXSLOT_{det,e}^c \quad \forall det, c \quad (2.4.3)$$

$$\sum_c EXSLOT_{det,e}^c \leq dem_{det}^e \quad \forall det, e \quad (2.4.4)$$

$$\sum_c ASSIGN_{g,b}^c \leq f_{g,b} \quad \forall g, b \quad (2.4.5)$$

$$DIFF_{g,b} \geq \sum_c ASSIGN_{g,b}^c - x_{g,b}^{old} \quad \forall g, b \quad (2.4.6)$$

$$DIFF_{g,b} \geq x_{g,b}^{old} - \sum_c ASSIGN_{g,b}^c \quad \forall g, b \quad (2.4.7)$$

$$\sum_{g,b} DIFF_{g,b} \leq 2 \cdot d_{max} \quad (2.4.8)$$

$$ASSIGN_{g,b}^c \in \{0, 1\} \quad \forall g, b, c \quad (2.4.9)$$

$$BILLET_{b,det}^c \in \{0, 1\} \quad \forall b, det, c \quad (2.4.10)$$

$$EXSLOT_{det,e}^c \geq 0 \quad \forall det, e, c \quad (2.4.11)$$

$$DIFF \geq 0 \tag{2.4.12}$$

The objective function in formulation ASMOD is the same as that in BALMOD. Constraint 2.4.0 indicates that each guard  $g$  with experience  $c$  is assigned to at most one billet  $b$ . Constraint 2.4.1 illustrates that each billet  $b$  is assigned at most one MSG  $g$  with experience  $c$ . Constraint 2.4.2 illustrates the flow conservation between the set of guard nodes and billet nodes in Figure 2.2. Constraint 2.4.3 represent the flow constraint between the set of billet nodes and detachment nodes in Figure 2.2. Constraint 2.4.4 shows that each detachment cannot receive more MSGs than available experience slots. Constraint 2.4.5 illustrates the value of the force/forbid matrix for that MSG-billet pair. Constraints 2.4.6 and 2.4.7 indicate the number of changes between the new assignment and the old assignment. Constraint 2.4.8 ensures that the maximum number of changes is less than the user-defined  $d_{max}$  value. (Note that changing the assignments of  $n$  MSG-billet pairs results in  $2n$  changes in the resulting assignment matrix.) Constraint 2.4.9 indicates that the assignment of MSG  $g$  with experience  $c$  to billet  $b$  can be either 0 or 1. Constraint 2.4.10 indicates that the assignment of experience  $c$  to billet  $b$  in detachment  $det$  can be either 0 or 1. Constraint 2.4.11 indicates that the assignment of experience  $c$  to an experience slot  $e$  in detachment  $det$  is greater than or equal to 0. Constraint 2.4.12 enforces the variable  $DIFF$  to be greater than or equal to 0.

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# CHAPTER 3:

## MARINE SECURITY GUARD ASSIGNMENT TOOL

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### 3.1 Purpose

The purpose of MSGAT is three-fold:

1. To streamline the information-exchange process between the Region Commands and MCESG assignment personnel;
2. To acquire all MSG and billet requirement information necessary to assign MSGs in accordance with the goal set in Table 2.2;
3. Provide an optimal assignment of MSGs to billets for each assignment cycle's 2/3 Poster Message, Final Message, and any message changes.

MSGAT accomplishes these objectives by automating the MCESG assignment cycle process. Specifically, the tool facilitates the creation of the following documents:

- Scrub List
- Post Requirements
- Post Choices
- Tentative Movement Message
- 2nd and 3rd Poster Message
- Final Message
- All variations of the movement messages.

The following sections explain the organization of MSGAT, the entry of MSG and billet information at the MCESG and region command levels, and the creation of all required messages.

## **3.2 Organization**

MSGAT is implemented in VBA because the Microsoft Office suite is installed on most computers within the Marine Corps. Additionally, the average administrative Marine is familiar with Excel, making it the ideal platform from which to base a decision support tool. MSGAT utilizes a hierarchy of workbooks to execute each assignment cycle. The MCEGS Master, Class Master, and Region Information workbooks comprise the tool.

### **3.2.1 MCEGS Master Workbook**

This workbook is used only by assignment personnel at MCEGS. The MCEGS Master workbook enables assignment personnel to:

- Change detachment information or add new detachments.
- Initiate new assignment cycles.

The manipulation of detachment information and the initiation of an assignment cycle are described in Section 3.3.1.

### **3.2.2 Region Information Workbooks**

The Region Information workbooks are used only by administrative personnel at each region. Every region receives their own Region Information workbook at the beginning of an assignment cycle. The Region Information workbooks are generated by the MCEGS Master workbook when an assignment cycle is initiated at the MCEGS level. The regions use these workbooks to complete the following:

- Scrub Lists
- Post Requirements
- Post Choices

Manipulation of the Region Information workbooks is described in Section 3.3.

### **3.2.3 Class Master Workbook**

The Class Master workbook is used only by MCESEG assignment personnel and is automatically generated by the MCESEG Master workbook at the initiation of a new cycle. This workbook preserves the functionality of the Region Information workbook and acts as the primary workbook in every assignment cycle. Specifically, the Class Master workbook enables assignment personnel to:

- Import Region information such as Scrub Lists, Post Requirements, or Post Choices.
- Build or edit Scrub Lists, Post Requirements, or Post Choices documents.
- Build or edit all 1st Poster information.
- Create and export the Tentative Movement Message, 2/3 Poster Message, and Final Message to the Region Information workbooks.

Manipulation of the Class Master workbook is explained in Section 3.3.

## **3.3 Assignment Cycle Walk-Through**

This section describes how MSGAT facilitates an assignment cycle from initiation to the release of the Final Movement Message and any message changes. This is an eight-step process that was designed to mirror the manual assignment process at MCESEG.

1. Assignment Cycle Initiation
2. Scrub List and Post Requirements
3. Tentative
4. Post Choices
5. 2/3 Poster Message
6. 1st Poster Information
7. Final Message
8. Message Changes



Two entities that have access to MSGAT: MCESEG assignment personnel and the region commands. MCESEG assignment personnel only manipulate the MCESEG Master workbook and the Class Master workbook. Region commands only manipulate the Region Information workbooks. This section describes the steps in the process as well as the responsibilities of MCESEG assignment personnel and the region commands.

### 3.3.1 Assignment Cycle Initiation

Detachment information is a critical aspect of every assignment cycle. Table 3.1 contains the detachment attributes. Information may change on a cycle by cycle basis; thus, MSGAT affords MCESEG the ability to alter detachment attributes at the beginning of every cycle. Values of detachment attributes have a direct impact on the resulting assignments. The remainder of this section discusses detachment attribute changes and assignment cycle initiation.

Table 3.1: The detachment attributes that require editing prior to initiating an assignment cycle.

<b>Attribute</b>	<b>Description</b>
Region	The identification code.
City	City location of the embassy.
Country	Country location of the embassy.
Tier	Tier level that this detachment has been assigned by the Department of State.
MCC	Four digit alpha-numeric identification code assigned by HQMC.
DC	Whether or not this detachment is located in a DC.
DetCmdr	DetCmdrs authorized by HQMC Table of Organization (T/O).
Watchstander	Watchstanders authorized by HQMC T/O.

#### **Location Information**

Detachments may be reassigned to different locations or regions altogether. In order to maintain the most current MCESEG climate, assignment personnel have the ability to relocate, rename, or even delete detachments.

#### **Tier Level Change**

The most common attribute change that is undergone by detachments is tier level. Detachment tier levels may be downgraded or upgraded depending on the amount of funding received from the Department of State (DoS 1999). For example, a detachment may be downgraded from tier level 1 to tier level 3. Altering tier level will affect MSG-billet assignments because MSGAT attempts to avoid sending MSGs to repeat tiers.

## **Staffing Level Change**

Change of detachment staffing levels is another common attribute change that occurs between assignment cycles. Although the number of DetCmdrs remain fairly constant, the number of T/O authorized watchstanders may change several times a year. As these numbers change, the number of watchstanders at each experience level at the detachment will also change. These changes have a direct impact on the MSG experience distribution at each detachment.

## **Initiation**

Once the detachment information is updated, MSGAT initiates the assignment cycle. Initiation involves creating the following set of Excel workbooks and files necessary for MSGAT to facilitate collection of information needed to execute the Balance Model. The region commands have no responsibility in the first step of the assignment cycle other than to receive their respective Region Information workbook via e-mail from assignment personnel. The following outline contains the hierarchy of workbooks and directories that are created during initiation.

### 1. Class Directory

(a) Class Master workbook

(b) Regions Directory

i. Region Information workbooks

(c) Solver Directory

i. Initial 2/3 Poster Message Solver Directory

A. Comma-separated-value (CSV) templates for saving all input data used to create the original 2/3 Poster Message.

ii. Initial Final Message Solver Directory

A. CSV templates for saving all input data used to create the original Final Message.

iii. Computational Infrastructure for Operations Research (COIN-OR) optimization files.

A. Dynamic linked library (DLL) files used by COIN-OR to formulate and solve the Balance Model.

### 3.3.2 Scrub Lists and Post Requirements

The data collection phase begins when MSGAT exports Region Workbooks to the region commands. MSGAT facilitates Scrub List creation at the regions. Table 3.2 contains the information that comprises each MSG's entry in the Scrub List.

Table 3.2: The data collected on each rotating MSG during the creation of the Scrub List.

<b>Attribute</b>	<b>Description</b>
Last	MSG's last name.
First	MSG's first name.
MI	MSG's middle initial.
Rank	MSG rank.
Sex	MSG gender.
SSgt Select	Is this MSG selected for the rank of SSgt?
DOR	Date of rank.
DCTB	Date current tour began.
RTD	Rotation tour date.
A/ Select	Is this MSG qualified to serve as an A/?
DC Qualified	Is this MSG qualified to serve in a DC?
Experience	The experience level of the MSG.
Company (CO)	MSG's current Region.
Platoon (PLT)	MSG's current detachment.
Tier	Tier level of the MSG's current detachment.
Prior Company	MSG's prior Region(s). Only available if the MSG is a 3rd Poster or 4th Poster.
Prior Platoon	MSG's prior detachment(s). Only available if the MSG is a 3rd or 4th Poster.
Prior Tier	Tier level of MSG's prior detachment(s). Only available if the MSG is a 3rd or 4th Poster.
Post Restriction	Region(s) that the MSG is unable to serve.

As regions collect Scrub List information, MSGAT also facilitates collection of information needed for the Post Requirements worksheet. This worksheet contains information on billets that need to be filled in the current assignment cycle. Table 3.3 contains the information that comprises each billet's entry in the Post Requirements worksheet.

Once the Scrub List and Post Requirements worksheets are complete, the regions send their Region Information workbooks back to MCESEG assignment personnel for compilation and creation of the Tentative Movement Message.

Table 3.3: The data collected on each rotating MSG during the creation of the Post Requirements.

<b>Attribute</b>	<b>Description</b>
Current MSG	MSG that currently fills this billet.
Region	Regional location of the billet's detachment.
Detachment	Detachment that houses this billet.
Tier	Tier level of this billet's detachment.
DC post	Is this billet located in a detachment within a DC?
Required Rank	Does this billet require a particular rank?
Need SSgt Select	Does this billet require an MSG selected for the rank of SSgt?
Required Experience	Does this billet require an MSG with a particular experience level?
Need A/	Does this billet require an MSG selected for A/?
Required Gender	Does this billet reside in a detachment which can house only males?
Current number of 1st Posters	How many 1st Posters are at this detachment, excluding any MSGs moving with the current assignment cycle?
Current number of 2nd Posters	How many 2nd Posters are at this detachment, excluding any MSGs moving with the current assignment cycle?
Current number of 3rd Posters	How many 3rd Posters are at this detachment, excluding any MSGs moving with the current assignment cycle?
Comments	Additional comments on the post requirements for this billet.

### 3.3.3 Tentative Movement Message

MSGAT uses the Scrub List and Post Requirement documents to create the Tentative Movement Message. Upon reception of the Region Information workbooks, MSGAT compiles the Scrub List and Post Requirements from each region into two master lists. MSGAT uses the master lists to create the Tentative Movement Message. Each entry in the Tentative Movement Message corresponds to a billet that needs to be filled during the current assignment cycle. Table 3.4 contains information found in the Tentative Movement Message. This information is also contained in the 2/3 Poster Message, and the Final Message. Therefore, some of the entries in the Tentative Movement Message will have an original value of to-be-determined (TBD) unless there has been a previous agreement to fill a billet. MSGAT exports the Tentative Movement Message to the Region Information workbooks. The regions use this information to create the Post Choices worksheet.

Table 3.4: The Tentative Movement Message exists to inform rotating MSGs of available billets and associated requirements.

<b>Item</b>	<b>Description</b>
Incoming MSG	MSG that is incoming to this billet. Unless there has been a previous agreement to fill the billet, this entry will be TBD.
Region	Regional location of the billet's detachment.
DC or A/	Is the incoming MSG DC qualified or designated as an A/?
To Post	Detachment that houses this billet.
From Post	The detachment that the incoming MSG is transferring from.
Replacing	The MSG being replaced.
SSgt Select	Is the incoming MSG selected for SSgt?
Incoming Experience	What is the experience level of the incoming MSG?
Post Requirements	What experience level was originally requested at this billet in the Post Requirements worksheet.

### 3.3.4 Post Choices

Region commands use the Tentative Movement Message to build the Post Choices worksheet. This worksheet consists of information from the Scrub List along with MSGs' detachment and region preferences. MSGAT allows MSGs to enter up to three detachment choices and two region choices. MSGs are restricted from selecting certain preferences for the following reasons:

- An MSG is unable to select a detachment that resides in one of their Post Restrictions.
- An MSG may not select a detachment for which they are unqualified. For instance, they may not select a detachment preference within a DC if they are not DC-qualified.
- An MSG is not able to serve in the same region more than once during their tour as an MSG. This avoids potential security risks that may arise (DoS 1999).
- An MSG may not select the same detachment for more than one detachment preference. Similarly, they may not select the same region for both region preferences. However, they are able to select a detachment and its corresponding region as a detachment and region preference, respectively.

Following completion of the Post Choices worksheet, MSGAT enables the regions to export updated Region Information workbooks to MCESG.

### 3.3.5 Second and Third Poster Movement Message

MCESG creates the initial 2/3 Poster Message once the Post Choices are received from the region commands. The creation of the 2/3 Poster Message consists of a five-step process.

1. Weight adjustment.
2. Forcing and forbidding MSG-detachment assignments.
3. CSV creation.
4. COIN-OR implementation.
5. Displaying results.

#### Weight Adjustment

MCESG assignment personnel begin the assignment creation process by adjusting the weight, or importance, of each attribute. Table 3.5 contains the attributes and the default weights that MSGAT takes into account when solving the Balance Model. MSGAT enables MCESG to adjust attribute weights based on guidance from the Commanding Officer.

Table 3.5: Attributes for each MSG-billet attribute pair and default weights used by MSGAT when solving the Balance Model. These weights are adjusted based on guidance from the Commanding Officer.

<b>Penalty</b>	<b>Default Weight</b>
<i>Rank</i>	5
<i>Preference</i>	5
<i>1/5-Fill</i>	20
<i>A/</i>	0
<i>Gender</i>	100
<i>Tier</i>	30
<i>Experience-Balance</i>	50
<i>Experience-Request</i>	50
<i>DC</i>	0
<i>SSgt-Select</i>	10

Attribute weights are used to assign penalties for each MSG-billet arc in the first layer of the Balance Model. Each attribute carries a penalty between 0 and 1, depending on the MSG-billet pair. If the pair results in a penalty, the penalty is multiplied by the weight of the violated attribute. The penalties for each attribute violation are described as follows:

- The *Rank* penalty is incurred if the rank of the MSG does not match the requested rank of the billet. The penalty increases as the difference in the MSG rank and billet-requested rank differs. For example, there is a larger penalty associated with assigning a Corporal to a Staff Sergeant billet than a Corporal to a Sergeant billet.
- The *Experience-Balance* penalty is incurred if the experience level of the MSG does not match the experience level needed at the embassy.
- The *Experience-Request* penalty is incurred if the experience level of the MSG does not match the experience level requested at the embassy. Although MSGAT balances MSG experience levels across detachments, embassies may also request MSGs with particular experience levels. MCESG can use attribute weights to determine the relative importance of overall experience balance and embassy requests.
- The *Preference* penalty is incurred if the billet is in an embassy that is not included in the MSG's detachment or Region preferences.
- The *1/5-Fill* penalty is incurred if the billet is not located in a 1/5 detachment. The purpose for the 1/5 fill penalty is to encourage the filling of all billets located in small detachments.
- The *A/* penalty is incurred if the billet is requesting an A/ and the MSG is not A/-qualified.
- The *Gender* penalty is incurred if the MSG's gender differs from the required gender at the billet.
- The *Tier* penalty is incurred if the billet's tier is the same as a tier in which the MSG has already served.
- The *Balance-experience* penalty is incurred if the billet has no demand for an MSG's specific experience level.
- The *DC* penalty is incurred if the billet is located in a DC and the MSG is not DC-qualified.
- The *SSgt-Select* penalty is incurred if the MSG is not a SSgt select and the billet is requesting an MSG that is selected.

Appendix A contains the penalty values for the various MSG-billet attribute pairs. MCESG has opted to assign A/ selected MSGs and DC designated MSGs manually. In this case, MCESG

can tune the  $A/$  and  $DC$  weights to 0. If MCESG assignment personnel choose to use MSGAT to make these assignments, then the weights can be increased to positive values.

### **Forcing and Forbidding MSG-Billet Assignments**

Following weight adjustment, MSGAT enables MCESG to force or forbid any MSG-billet assignments. MCESG can choose to force or forbid as many assignments as they like, however MSGAT will verify whether or not MCESG's constraints have made the resulting problem infeasible. MCESG has the ability to create infeasibility by committing one or more of the following:

- MCESG may force and forbid an MSG to the same detachment. In this case, MSGAT will require MCESG to choose a preferred action before proceeding.
- MCESG may attempt to force more MSGs to a detachment than there are billets available at that detachment. MSGAT will not permit the assignment of more MSGs than there are billets available at any detachment.

### **CSV Creation**

MSGAT creates the following CSV files to solve the assignment problem and record input data for future reference.

- $G$ : set of all MSGs.
- $B$ : set of all billets.
- $D$ : set of all detachments.
- $E$ : set of all experience levels.
- $G_e$ : set of MSGs with experience level,  $e$ .
- $B_{det}$ : set of billets located in detachment,  $det$ .
- $Weights$ : set of attribute weights utilized in this assignment.
- $f_{g,b}$ : the force/forbid matrix.
- $dem_e^{det}$ : experience level  $e$  demanded by detachment  $det$ .



- $cost_{g,b}$ : calculation of the MSG-billet cost for every MSG-billet pair and creation of the cost matrix.

### COIN-OR Implementation

Formulations BALMOD and ASMODIFY are relatively straightforward to formulate and solve as integer linear problems in GAMS or a similar commercial solver. However, MCESEG needs an open source, stand-alone solver to avoid licensing fees and training associated with commercial solvers. The COIN-OR project provides open source optimization software for the operations research community (Hunsaker 2011). The COIN-OR solver used in MSGAT is the COIN-MP (COIN Mixed Program) solver. COIN-MP generates a COIN-MP DLL library and uses the branch and bound algorithm to solve integer linear problems (Hunsaker 2011).

### Displaying Results

The CSV input files and the resulting assignment message are stored in the current assignment's folder within the Solver directory. The assignment message is stored in matrix form and is called  $x_{g,b}^{old}$ . Each MSG is a row entry and each billet is a column entry in this matrix. For example, the assignment of MSG "A" to billet "A101" results in an entry of 1 for the  $x_{A,A101}^{old}$  field. The matrix  $x_{g,b}^{old}$  will be referred to if an assignment is modified, as described in Sections 3.3.8 and B.4. MSGAT exports the completed 2/3 Poster Message to the Region Information workbooks. The regions review the 2/3 Poster Message and petition MCESEG for changes as needed.

### 3.3.6 First Poster Information

To continue the assignment cycle, MCESEG collects information from MSGs currently at MSG school and scheduled to rotate in the current assignment cycle as 1st Posters. This information is used when creating the Final Message. Table 3.6 contains the information collected on 1st Posters. Information from 1st Posters consists of all 2/3 Poster information other than prior detachments and preferences. MCESEG policy states that 1st Posters are not afforded the option to choose detachment preferences, but they are able to choose region preferences (Krulak 1999).

### 3.3.7 Final Movement Message

MCESEG uses 1st Poster information and the 2/3 Poster Message to create the Final Message. The steps involved in this process are as follows:

1. Selection of official 2/3 Poster Message.

Table 3.6: Information on 1st Posters is collected in order to create the Final Message.

<b>Item</b>	<b>Description</b>
Last	MSG's last name.
First	MSG's first name.
MI	MSG's middle initial.
Rank	MSG rank.
Sex	MSG gender.
SSgt Select	Is this MSG selected for the rank of SSgt?
DOR	Date of rank.
DCTB	Date current tour began.
RTD	Rotation tour date.
A/ Select	Is this MSG qualified to serve as an A/?
DC-qualified	Is this MSG qualified to serve in a DC?
Post Restriction	Region(s) that the MSG is unable to serve.
Region Preferences	MSG regional command preferences.

2. Weight adjustment.
3. Forcing and forbidding MSG-billet assignment
4. CSV creation.
5. COIN-OR implementation.
6. Displaying results.

### **Selection of 2/3 Poster Message**

Prior to creating the Final Message, MSGAT requires an official 2/3 Poster Message from which to base the Final Message. Selection of an official 2/3 Poster Message will initialize the force and forbid matrices for the Final Message. That is, all 2/3 Posters assigned in the official 2/3 Poster Message will be forced to the billets they were assigned to and forbidden from all other billets. The reason for this is that the release of the Final Message occurs during the movement period for all 2/3 Posters. It is impractical to reassign 2/3 Posters as they are rotating.

### **Weight Adjustment**

Initially, MSGAT uses the same weights that were used to create the official 2/3 Poster Message. These weights are described in Section 3.3.5. MCESEG may adjust the weights if needed.

### **Forcing and Forbidding MSG-Billet Assignments**

Following weight adjustment, MSGAT enables MCESEG to force or forbid MSG-billet assignments. The force/forbid matrices are pre-formulated upon selection of the official 2/3 Poster Message. MCESEG is able to make necessary changes, even if it involves altering the pre-formulated force/forbid matrices. The possibility of infeasibility still exists however, so MSGAT provides the same checks on the matrices as described in Section 3.3.5.

### **CSV Creation**

MSGAT creates the same CSV files for the Final Message that were created for the official 2/3 Poster Message; however, some of the CSV files may differ based on adjustments made in the input data.

### **COIN-OR Implementation**

Implementation via the COIN-MP solver is described in Section 3.3.5.

### **Displaying Results**

The CSV input files and the resulting Final Message are stored in the current assignment's folder within the Solver directory. The Final Message is stored in the form of a matrix called  $x_{gb}^{old}$ , with each MSG as a row entry and each billet as a column entry. MSGAT exports the completed Final Message to the Region Information workbooks. The regions review the Final Message and petition MCESEG for changes if needed.

## **3.3.8 Movement Message Changes**

Movement message changes arise in one of two forms: Message Modifications and Official Message Changes. This section describes each type of movement message change.

### **Message Modifications**

Message Modifications occur after MSGAT has created a 2/3 Poster Message or Final Message, but before the declaration as an official message. Assignment messages are declared official when they are exported to the Region Information workbooks. MSGAT permits assignment modification in various ways.

- Adjustment of attribute weights.
- Alteration of input data, e.g., Scrub List, Post Requirements, or Post Choices information.
- Deletion or addition of MSGs or billets.

- Alteration of the force/forbid matrix.

### **Official Message Changes**

It is not uncommon for 2/3 Poster Messages or Final Messages to undergo a series of official message changes during an assignment cycle. These changes usually involve the manipulation of several MSG-billet assignments. MSGAT enables MCESEG to execute message changes in one of three ways.

1. Changing the force/forbid matrix.
2. Changing attribute weights.
3. A combination of force/forbid matrix changes and attribute weight changes.

The user-defined parameter  $d_{max}$  places a limit on the number of changes between the old assignment and new assignment, as described in Section 2.3

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# CHAPTER 4:

## RESULTS

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This chapter examines the performance of MSGAT using historical MSG and billet data from five previous assignment cycles. Section 4.1 compares assignments produced by MSGAT to the MCESG's manually-generated assignment using the following measures of effectiveness (MOEs):

1. Percentage of billets needing an A/ qualified MSG that receive an A/. Although MCESG prefers to manually assign A/ qualified MSGs, historical data suggests that they are unable to assign all A/ qualified MSGs to billets requesting an A/. A high percentage of billets receiving the requested A/ is preferred over a low percentage.
2. Percentage of 1/5 posts that receive an MSG. A 1/5 post is a post with one DetCmdr and five watchstanders. These posts have the fewest number of MSGs assigned to them, and filling a billet in a 1/5 post is preferred over filling a billet in a post with more MSGs. Thus, a higher percentage of 1/5 posts receiving an MSG is preferred over a low percentage.
3. Percentage of billets that received a requested experience level. Although MSGAT attempts to balance experience level across detachment, detachments are also able to request particular experience levels. MCESG did not document the number of 1st, 2nd, and 3rd Posters at each detachment in any of the assignment cycles. Therefore, it is not possible to evaluate the degree to which experience levels were balanced among detachments. Thus, this MOE measures the number of billets that received a requested MSG experience level. A higher percentage of billets receiving a requested experience level is preferred over a low percentage.
4. Percentage of MSGs that are assigned to a nonrepeat tier. A higher percentage of MSGs assigned to a nonrepeat tier is preferred over a low percentage.
5. Percentage of billets that receive a requested rank. A higher percentage of billets receiving a requested rank is preferred to a low percentage.
6. Percentage of MSGs that receive a detachment preference. A higher percentage of MSGs receiving a billet in a preferred detachment is preferred over a low percentage.

Table 4.1: Description of MSG data provided by MCESG for the historical comparisons.

<b>Datum</b>	<b>Description</b>
Identification	MSG's first and last names.
Rank	MSG rank.
Experience	Experience level.
DOR	Date of rank.
A/ select	Approved for A/ duty.
Experience	The experience level of the MSG.
CO	MSG's current Region.
PLT	MSG's current detachment.
Tier	Tier level of current detachment.
Prior CO	MSG's prior Region.
Detachment preferences	Top three detachment requests.
Region preferences	Top two Region requests.

Table 4.2: Description of the billet data provided by MCESG for the historical comparisons.

<b>Datum</b>	<b>Description</b>
Region	Regional command where the billet is located.
Detachment	Detachment where the billet is located.
Requested rank	The rank of MSG requested by the billet.
Requested experience	The experience level of MSG requested by the billet.
Need A/	Whether the billet requires an A/-qualified MSG.
Need DC	Whether the billet is located in a DC.
Tier	Tier classification of the parent detachment.
1/5	Whether this billet is located in a 1/5 post.

- Percentage of MSGs that receive a Region preference. A higher percentage of MSGs receiving a region preference is preferred over a low percentage.

## 4.1 Historical Assignment Comparison

To facilitate comparison of MSGAT with manual assignments, MCESG provided Scrub List, Post Requirements, and Post Choices data from assignment cycles 4-10, 5-10, 1-11, 2-11, and 3-11, as well as the manual assignments that were ultimately made in those cycles. Tables 4.1 and 4.2 contain descriptions of the information provided.

Historically, MCESG has not had a standardized data collection process. As a result, not every type of MSG and billet data is available for every cycle. Thus, assignment quality cannot be compared using all MOEs for every assignment cycle.

### 4.1.1 Attribute Weights

To analyze the performance of MSGAT, four assignments were generated for each assignment cycle. Assignments differ in the weights that are assigned to each attribute. Table 4.3 contains these weights. As discussed in Chapter 2, attribute weights signify the importance of each attribute. A higher weight indicates a more important attribute. Each assignment uses a set of attribute weights designed to favor a particular entity within the MCESG organization. The *MCESG standard* assignment reflects the decision process and attribute priorities that MCESG personnel currently use when creating assignments. This set of attribute weights was determined in discussions with assignment personnel at MCESG. The *MSG-centric* assignment is constructed with attribute weights that favor the MSG interests such as the MSG’s region and detachment preferences. The *Region-centric* assignment emphasizes attributes that favor region interests, such as experience and rank. The *Headquarters (HQ)-centric* assignment emphasizes attributes important at the HQ level of MCESG, such as assigning MSGs to nonrepeat tiers.

Table 4.3: Attribute weights for each of the four assignment cases. The Gender, DC, SSgt Select, and Experience-Balance attribute weights are set to 0 because this data is not documented for any of the historical assignment cycles.

<b>Attribute</b>	<b><i>MCESG standard</i></b>	<b><i>MSG-centric</i></b>	<b><i>Region-centric</i></b>	<b><i>HQ-centric</i></b>
A/	100	90	100	100
1/5	70	70	70	70
Tier	40	5	5	40
Experience-Request	20	15	25	15
Rank	5	15	30	5
Preferences	5	50	5	5
Gender	0	0	0	0
DC	0	0	0	0
SSgt Select	0	0	0	0
Experience-Balance	0	0	0	0

### 4.1.2 Analysis

This section examines MOE satisfaction using MSGAT compared to the MCESG-generated manual assignments. In addition to the attribute weights described in Section 4.1.1, several “single-MOE” assignments were generated for each set of assignment cycle data. The single-MOE assignments were created in order to determine the maximum possible satisfaction of each MOE in each assignment cycle; in other words, to determine an upper bound on performance.



In single-MOE assignments, all attribute weights are equal to zero other than the weight for the MOE being optimized. Table 4.4 contains the results of the single-MOE assignments.

Table 4.4: Each MOE attribute is optimized for every set of assignment cycle data.

Cycle	Attribute	Percent satisfaction in single-MOE assignments
4-10	A/ Billets	100
	1/5 Billets	98.9
	Billet Experience Request	26.6
	MSG to Different Tier	92.5
	Billet Rank Request	31.3
	MSG Preference	83.1
5-10	A/ Billets	85.7
	1/5 Billets	92.2
	Billet Experience Request	N/A
	MSG to Different Tier	94.2
	Billet Rank Request	N/A
	MSG Preference	81.9
1-11	A/ Billets	100
	1/5 Billets	95.2
	Billet Experience Request	24.8
	MSG to Different Tier	N/A
	Billet Rank Request	N/A
	MSG Preference	71.8
2-11	A/ Billets	N/A
	1/5 Billets	N/A
	Billet Experience Request	29.6
	MSG to Different Tier	100
	Billet Rank Request	48.9
	MSG Preference	86.7
3-11	A/ Billets	N/A
	1/5 Billets	98.5
	Billet Experience Request	26.8
	MSG to Different Tier	N/A
	Billet Rank Request	N/A
	MSG Preference	N/A

### **Billets Requiring A/ MSGs**

Information on A/-qualified MSGs was not documented for assignment cycles 2-11 and 3-11. Comparison of this MOE is conducted for cycles 4-10, 5-10, and 1-11. Figure 4.1 represents the

percentage of billets requesting an A/ that receive an A/-qualified MSG. MSGAT assignments

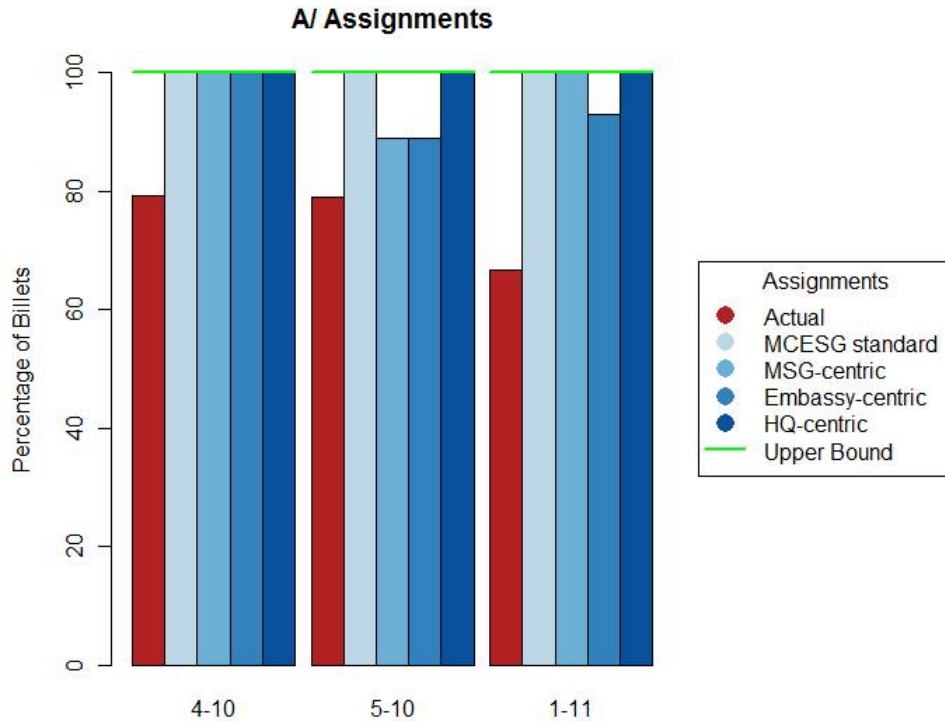


Figure 4.1: The percentage of billets requesting an A/ that receive an A/-qualified MSG in the 4-10, 5-10, and 1-11 assignment cycles. The maximum possible percentage of billets that could receive an A/-qualified MSG for each class is indicated by the upper bound in green.

assign more A/-qualified MSGs than the manual assignment in every historical comparison. In the 4-10 comparison, MSGAT satisfies the maximum percentage of billets requesting an A/ for every MSGAT assignment. The manual 4-10 assignment satisfies only 78% of billets requesting an A/. In the 5-10 comparison, MSGAT satisfies the maximum percentage of the billets with the *MCESG standard* and *HQ-centric* assignments. The *MSG-centric* and *Embassy-centric* assignments satisfy 92% of the billets while the manual assignment fills only 77%. In the 1-11 comparison, the manual assignment satisfies only 67% of billets requesting an A/. The *MCESG standard*, *MSG-centric*, and *Embassy-centric* assignments each satisfy the maximum percentage of the A/-requesting billets.

## Billets at 1/5 Posts

Figure 4.2 illustrates the fill percentage of billets filled at 1/5 posts. This percentage was documented during cycles 4-10, 5-10, 1-11, and 3-11. MSGAT assignments fill more billets at

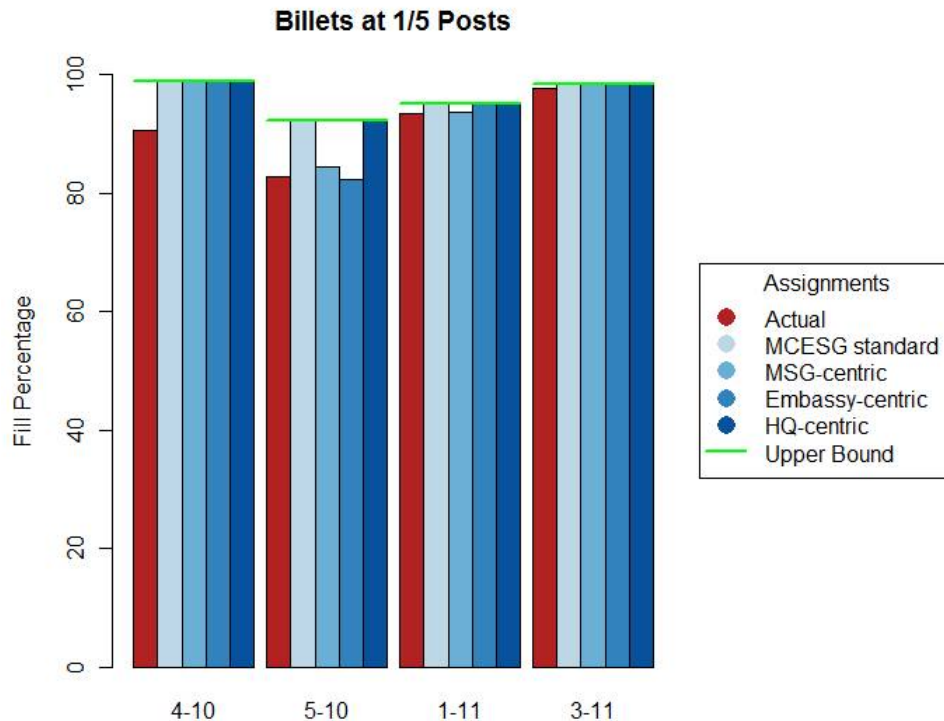


Figure 4.2: The percentage of billets at 1/5 posts that are filled in the 4-10, 5-10, 1-11, and 3-11 assignment cycles. The maximum possible percentage of 1/5 billets that could be filled is indicated by the upper bound in green.

1/5 posts for almost every assignment cycle comparison. In the 4-10 comparison, every MSGAT assignment results in the maximum percentage of 1/5 billets being filled while the manual assignment assigns only 92%. In the 5-10 comparison, the *MCESG standard* and *HQ-centric* assignments each satisfy the maximum percentage of 1/5 billets. The *MSG-centric* and *Embassy-centric* assignments result in 83% and 81% of 1/5 posts being assigned, respectively. The manual assignment for 5-10 results in 81% of 1/5 billets being filled. The 1-11 manual assignment assigns 93% of 1/5 billets while the *MCESG standard*, *Embassy-centric*, and *HQ-centric* assignments satisfy the maximum percentage of 1/5 billets, respectively. The manual assignment performs the best in cycle 3-11, assigning 98% of 1/5 billets. However, all 3-11 MSGAT assignments outperform the manual assignment by assigning the maximum possible percentage of 1/5 billets.

## Nonrepeat Tier

Figure 4.3 represents the percentage of Marines assigned to a nonrepeat tier. MSG data on prior assignments was not documented for assignment cycles 1-11 and 3-11. With respect to the

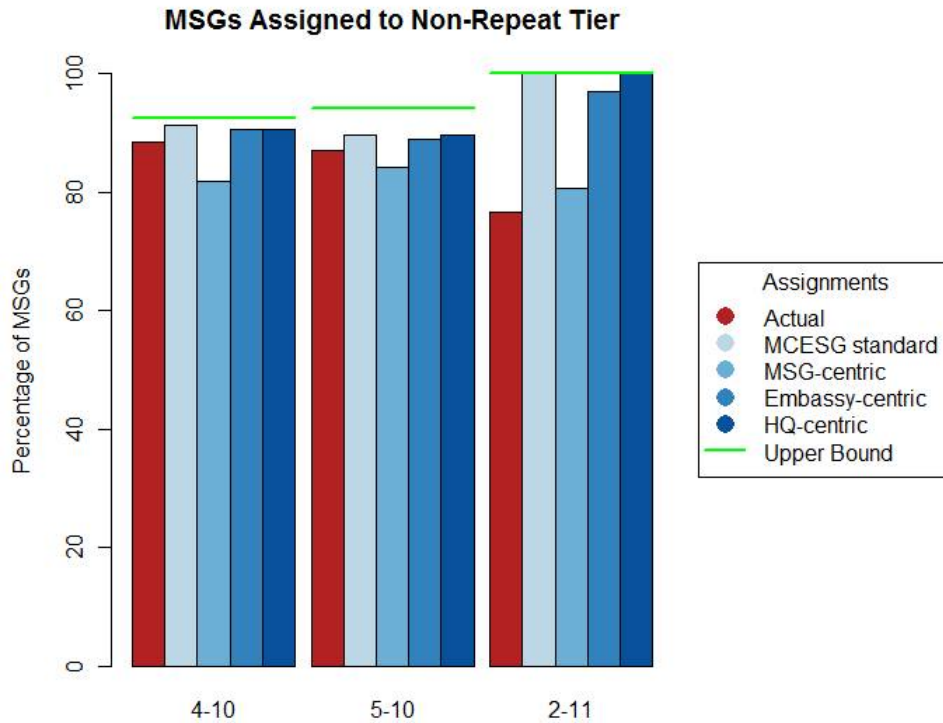


Figure 4.3: The percentage of MSGs assigned to nonrepeat tiers in the 4-10, 5-10, and 2-11 assignment cycles. A higher percentage of MSGs assigned to a nonrepeat tier is preferred over a low percentage. The maximum possible percentage of MSGs that could be assigned to a nonrepeat tier is indicated by the upper bound in each cycle.

MSGAT assignments, the *MSG-centric* assignment produces solutions that assign lower percentage of MSGs to a nonrepeat tier level in all cycles. Excluding the *MSG-centric* assignment, the manual assignment results in the lowest percentage of MSGs being assigned to a nonrepeat tier for every cycle. In assignment cycle 4-10, the *MCESG standard*, *Embassy-centric*, and *HQ-centric* assignments outperform the manual assignment and assign nearly the maximum possible percentage of MSGs to a nonrepeat tier level. The manual assignment is slightly outperformed by the MSGAT assignments in cycle 5-10; however, all assignments assign nearly the maximum possible number of MSGs to nonrepeat tiers. In assignment cycle 2-11, the manual assignment results in only 75% of MSGs being assigned to a nonrepeat tier level. The *MCESG*

*standard* and *HQ-centric* assignments result in the maximum percentage of MSGs assigned to a nonrepeat tier level.

### Requested Experience Level

MCESG did not document the number of 1st, 2nd, and 3rd Posters at each detachment in any of the assignment cycles. Therefore, it is not possible to evaluate the degree to which experience levels were balanced among detachments. Instead, this comparison examines the percentage of billets that received a requested MSG experience level and is illustrated in Figure 4.4. The man-

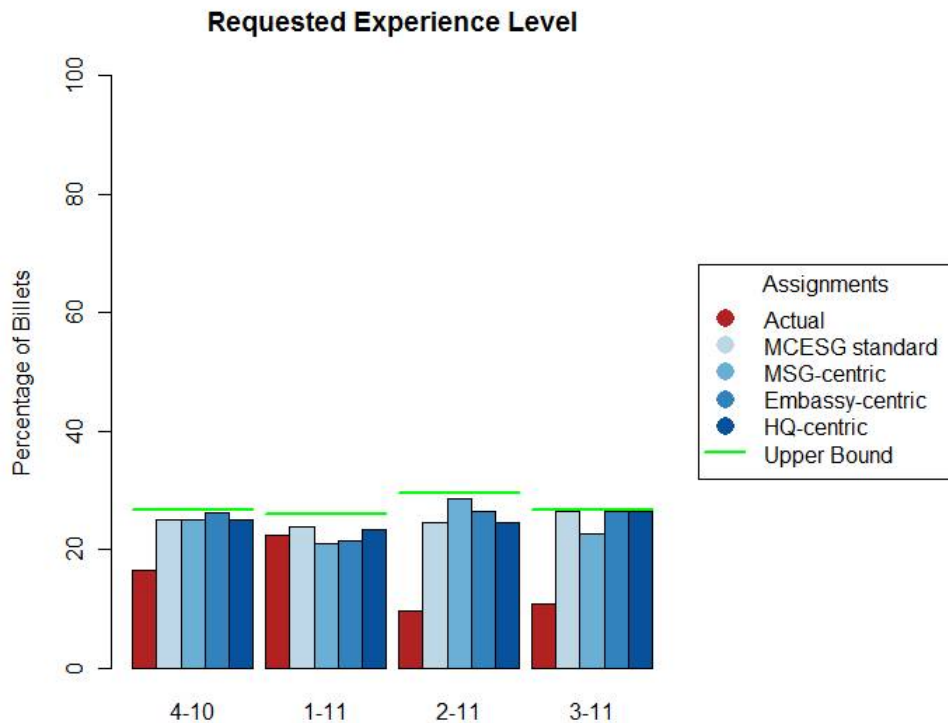


Figure 4.4: The percentage of billets that received their requested MSG experience level in the 4-10, 1-11, 2-11, and 3-11 assignment cycles. A higher percentage of billets receiving a requested MSG experience level is preferred over a low percentage. The upper bound represents the maximum percentage of billets that could receive a requested experience level.

ual 4-10 assignment is outperformed by all 4-10 MSGAT assignments. The *Embassy-centric* assignment results in the maximum percentage of billets receiving a requested experience level. All 1-11 MSGAT assignments nearly satisfy the maximum possible percentage of billet experience requests. In the 2-11 historical comparison, the manual assignment is significantly outperformed by all 2-11 MSGAT assignments. The *MSG-centric* assignment for 2-11 satisfies

nearly the maximum percentage of billet experience requests. The manual assignment is also significantly outperformed in the 3-11 historical comparison. In this cycle, the *MCESG standard*, *Embassy-centric*, and *HQ-centric* assignments all satisfy nearly 100% of the experience requests.

### Requested Rank

Billet rank requests were not documented for assignment cycles 5-10, 1-11, and 3-11. Figure 4.5 depicts the percentage of billets that received a requested MSG rank for cycles 4-10 and 2-11.

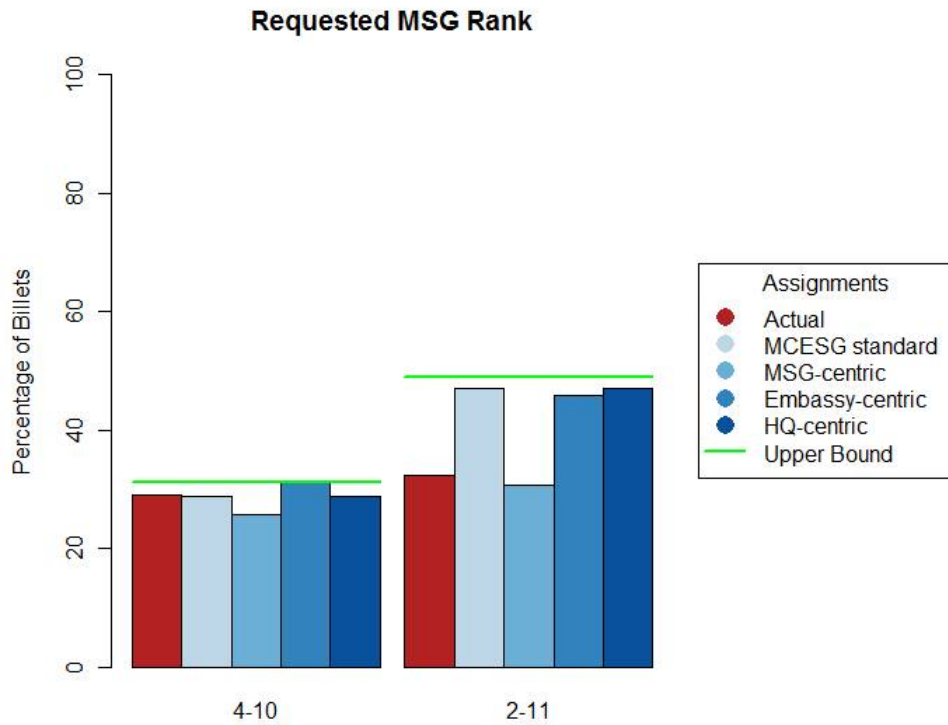


Figure 4.5: The percentage of billets that received their requested MSG rank in the 4-10 and 2-11 assignment cycles. A higher percentage of billets receiving a requested MSG rank is preferred over a low percentage. The upper bound represents the maximum percentage of billets that could receive a rank request.

The 4-10 manual assignment satisfies nearly the maximum possible percentage of rank requests, but is outperformed by the *Embassy-centric* assignment. The *Embassy-centric* assignment satisfies the maximum percentage of rank requests. The 2-11 manual assignment is outperformed

by the *MCESG standard*, *Embassy-centric*, and *HQ-centric* assignments. Each of these 2-11 MSGAT assignments nearly satisfies the maximum percentage of rank requests.

### MSG Preferences

Detachment preferences were not recorded for MSGs rotating during assignment cycle 3-11. The percentage of MSGs that received a detachment preference is displayed in Figure 4.6.

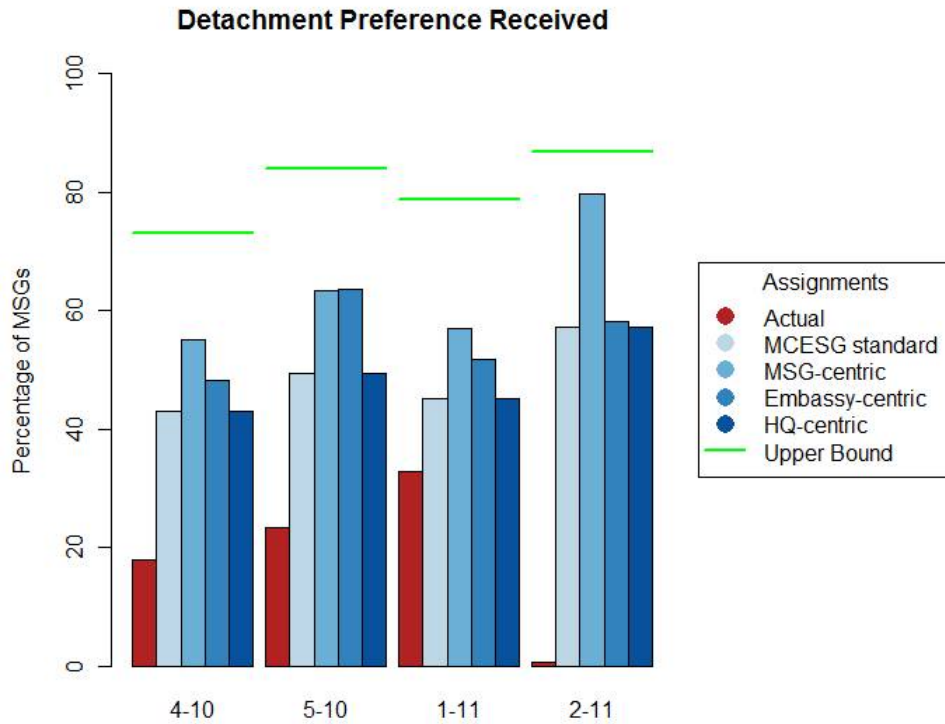


Figure 4.6: The percentage of MSGs that receive a detachment choice. A higher percentage of MSGs receiving a detachment choice is preferred over a low percentage. The upper bound represents the maximum percentage of MSGs that could receive a detachment preference.

As expected, the *MSG-centric* assignment generates the highest percentage of MSGs whose detachment preferences are satisfied, although other MSGAT assignments also assign a high percentage of MSGs a preferred detachment. The 4-10, 5-10, 1-11, and 2-11 manual assignments assign only 18%, 23%, 33%, and 1% of MSGs to a preferred detachment. With the exception of the 1-11 cycle, the manual assignments are significantly outperformed by MSGAT assignments. The *MSG-centric* assignment from cycle 2-11 results in the highest percentage of MSGs receiving a detachment preference.

Figure 4.7 depicts the percentage of MSGs that receive a region command preference. In contrast to Figure 4.6, the *MSG-centric* assignments do not always result in the highest number of MSGs receiving a region preference. This happens because in the *MSG-centric* weight set, the preference attribute is given the highest weight with respect to the other weight sets. The preference weights and penalties are organized such that MSGAT assigns an MSG to a detachment preference before a region preference. The MSG preference penalty is described in Appendix A. Thus, the *MSG-centric* weight set has a higher number of MSGs going to a detachment preference than a region preference. The manual assignments result in the lowest percentage of MSGs receiving a region command preference for every historical comparison.

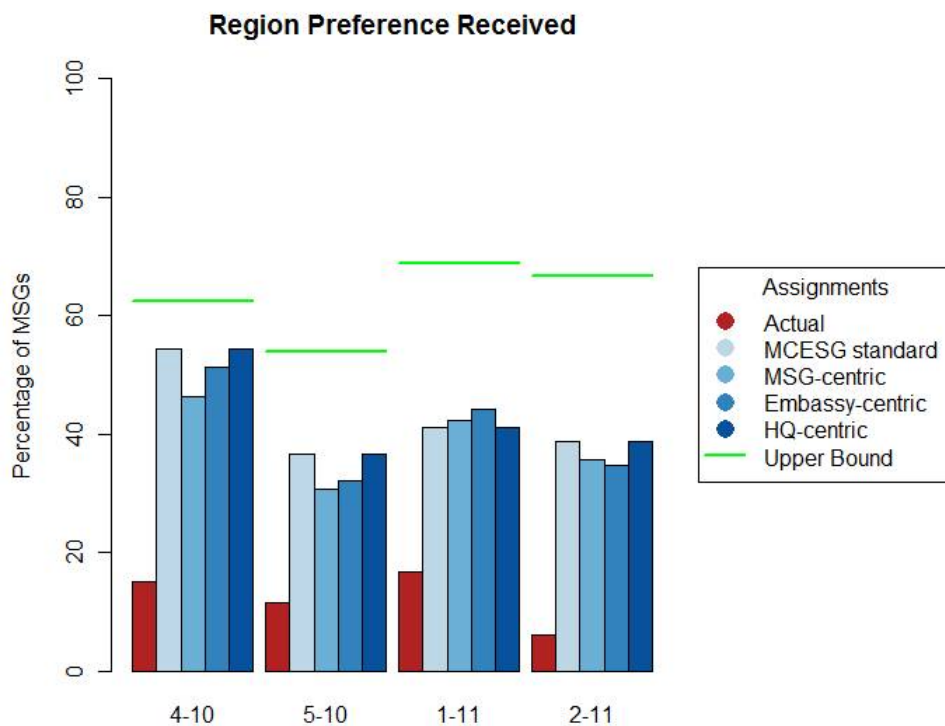


Figure 4.7: The percentage of MSGs that receive a region choice. A higher percentage of MSGs receiving one region choice is preferred over a low percentage. The upper bound represents the maximum percentage of MSGs that could receive a region preference.

The summary of overall preference satisfaction is shown in Figure 4.8. This figure indicates the percentage of MSGs that are assigned to at least one of their preferences. The manual assignment is outperformed significantly by the MSGAT assignments in every historical comparison. Although satisfying MSG preferences is not necessarily a top priority for MCESG, these results



demonstrate that it is possible to satisfy many MSGs' preferences without sacrificing solution quality with regard to the other MOEs.

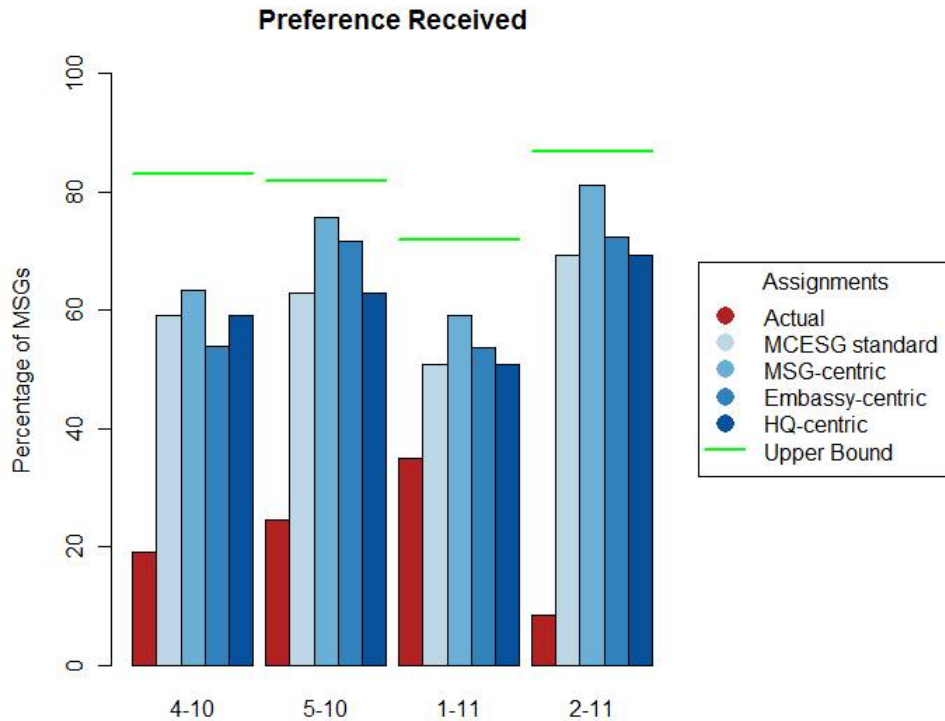


Figure 4.8: The percentage of MSGs that receive at least one preference. A higher percentage of MSGs receiving a preference is preferred over a low percentage. The upper bound represents the maximum percentage of MSGs that could receive a detachment or region preference.

## 4.2 Discussion

MSGAT assignments provide solutions that result in a higher overall satisfaction level than manually generated assignments. In nearly all historical comparisons, the manual assignment is significantly outperformed by every MSGAT assignment with respect to every MOE. For these historical comparisons, standard MCESG procedure is followed by assigning 2nd and 3rd Posters separately from 1st Posters. Even better results could be achieved by waiting for 1st Poster information and assigning all MSGs at once.

It is also important to consider the time required to produce an assignment. The time taken to enter the data into the decision support tool was approximately 12 hours of work, by one individual. Once the data was entered and the the problem formulated, the computational time

was approximately 30 seconds. This can be compared with the 1,200 hours it takes for three Marines within the assignments section at MCESG to enter the data and reach a viable solution. Additionally, the time taken to generate a second solution with MSGAT is very low; usually on the order of 60–120 seconds. This can be compared with the 1–2 weeks required for assignment personnel to generate a second solution.

The main finding of this analysis is that MSGAT is able to provide solutions that satisfy the MOEs more favorably than the manual assignment process at MCESG for data from most historical assignment cycles. The decision support tool provides “better-fitting” assignments using fewer resources, and in a shorter time period than the current manual assignment process.

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# CHAPTER 5:

## CONCLUSION AND RECOMMENDATIONS

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This thesis presents a personnel assignment tool called the Marine Security Guard Assignment Tool (MSGAT). MSGAT is an Excel-based decision support tool that utilizes a system of workbooks to guide assignment personnel through a streamlined data collection process. Once MSG and billet data are collected, MSGAT implements an integer linear program to optimally assign MSGs to billets while balancing MSG experience across embassies.

MSGAT offers the user a great deal of power over the assignment process. In particular, MSGAT

- Allows the user to adjust attribute weights when making assignments;
- Affords the user the ability to force or forbid specific MSG-billet assignments; and
- Incorporates a persistent assignment modification feature in which the user can control the number of changes in an assignment relative to an existing assignment.

MSGAT utilizes formulations BALMOD and ASMOD to generate assignments. These formulations are derived from a two layer multicommodity network called the Balance Model, in which MSG experience level serves as the commodity. Formulation BALMOD is the formulation primarily used by MSGAT when making assignments. Formulation ASMODIFY is used when modifying official assignments and allows MCESEG to control the number of changes in an assignment relative to an existing assignment.

To validate MSGAT and illustrate its usefulness in facilitating the assignment cycle process, this thesis examines MSGAT performance compared to historical manual assignment results from classes 4-10, 5-10, 1-11, 2-11, and 3-11. MSGAT uses actual MSG and billet data to generate assignments for each cycle using four sets of attribute weights. Assignments produced by MSGAT are superior to the manual assignments on nearly all MOEs for every historical comparison.

Not only does MSGAT outperform the manual assignments with respect to overall MOE satisfaction, but it also significantly reduces the amount of time spent by MCESEG when executing

assignment cycles. Prior to MSGAT, a typical manual assignment involving roughly 300 MSGs to 149 embassies took three Marines in the MCESEG Assignments section approximately 1,200 hours to complete. Included in this 1,200 hours is the 3 weeks it takes to calculate an assignment. MSGAT has reduced the total assignment cycle time by 80%, down to 240 hours. Moreover, MSGAT has reduced the assignment calculation time from 3 weeks down to 30 seconds.

## **5.1 Implementation**

As of June 2011, MSGAT is in use at MCESEG. The data collection functionality of MSGAT was used to collect MSG and billet information for the creation of the Scrub List, Post Requirements, and Post Choices documents during the 3-11 and 4-11 assignment cycles. Additionally, MSGAT will be calculating assignment solutions alongside the MCESEG assignments section during the 4-11 assignment cycle. Solutions achieved by MSGAT are expected to be implemented by MCESEG. Full MSGAT implementation is forecasted for the 5-11 assignment cycle. Data collection for the 5-11 cycle begins in July 2011.

## **5.2 Future Work**

The Marine Corps Total Force System (MCTFS) is the integrated personnel and pay system that supports the USMC (Jones 2001). MCTFS utilizes a single database to maintain personnel records of Marines. Integration of MSGAT with MCTFS would expedite the data collection process even further.

Marine Corps Enterprise Information Technology Services (MCEITS) is a core capability that enables access to information by providing the ability to collaborate and share information across USMC domains (Crow 2007). MCEITS maintains a Sharepoint site that is used extensively by MCESEG personnel. Movement of MSGAT onto the MCESEG Sharepoint site and development of a Web interface would improve the assignment cycle process.

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# APPENDIX A:

## MSG AND BILLET ATTRIBUTE PENALTIES

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This appendix contains the MSG and billet attribute penalty pairs utilized by MSGAT.

Table A.1: Attributes for each MSG-billet attribute pair and default weights used by MSGAT. Note, A/ and DC weights are set to 0 because these assignments are not conducted by MSGAT. MCESG Assignments conducts these assignments manually.

<b>Penalty</b>	<b>Default Weight</b>
<i>Preference</i>	5
<i>Tier</i>	30
<i>Gender</i>	100
<i>1/5-Fill</i>	20
<i>A/</i>	0
<i>Experience-Balance</i>	50
<i>Experience-Request</i>	50
<i>DC</i>	0
<i>SSgt-Select</i>	10
<i>Rank</i>	5

Table A.2: Definition of the MSG preference penalty  $v_{g,b}^{Pref}$ , for the assignment of MSG  $g$  to billet  $b$ .

<b>Detachment Choice Received</b>	<b>Region Choice Received</b>	$v_{g,b}^{Pref}$
1	Any	0
2	Any	0.1
3	Any	0.2
None	1	0.3
	2	0.4
None	None	1



Table A.3: Definition of the penalty  $v_{g,b}^{Tier}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the MSG has already served at the same tier as that of billet  $b$ .

MSG's Previous Tier	MSG's Current Tier	Billet Tier	$v_{g,b}^{Tier}$	
None	None	1	0	
		2	0	
		3	0	
	1	1	1	1
			2	0
			3	0
	2	2	1	0
			2	1
			3	0
	3	3	1	0
			2	0
			3	1
1	1	1	1	
		2	0.8	
		3	0	
	2	2	1	1
			2	0.8
			3	0
	3	3	1	0.5
			2	0
			3	0.8
2	1	1	1	
		2	0.8	
		3	0	
	2	2	1	0.8
			2	1
			3	0.5
	3	3	1	0
			2	0.5
			3	0.8
3	1	1	0.8	
		2	0	
		3	0.5	
	2	2	1	0
			2	0.8
			3	0.5
	3	3	1	0.5
			2	0.8
			3	1

Table A.4: Definition of the penalty  $v_{g,b}^{Gender}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the MSG is a different gender than the billet is requesting.

Gender requested at billet.	MSG gender.	$v_{g,b}^{Gender}$
None	Female	0
	Male	0
Female	Female	0
	Male	1
Male	Female	1
	Male	0

Table A.5: Definition of the penalty  $v_{g,b}^{15}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the billet is located in a 1/5 post and this billet goes unfilled.

Is billet in a 1/5 post?	Does billet receive MSG?	$v_{g,b}^{15}$
No	No	0
	Yes	1
Yes	No	0
	Yes	0

Table A.6: Definition of the penalty  $v_{g,b}^{A/}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the billet is requesting an A/ and MSG is not A/-qualified.

Is billet requesting A/?	Is MSG A/ qualified?	$v_{g,b}^{A/}$
No	No	0
	Yes	0
Yes	No	1
	Yes	0

Table A.7: Definition of the penalty  $v_{g,b}^{ExpReq}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the billet does not receive a requested experience level.

<b>Billet Request</b>	<b>MSG Experience</b>	$v_{g,b}^{ExpReq}$
1st Poster	1st Poster	0
	2nd Poster	0.5
	3rd Poster	1
2nd Poster	1st Poster	0.5
	2nd Poster	0
	3rd Poster	0.7
3rd Poster	1st Poster	1
	2nd Poster	0.5
	3rd Poster	0
Any	1st Poster	0
	2nd Poster	0
	3rd Poster	0

Table A.8: Definition of the penalty  $v_{g,b}^{DC}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the billet is located in a DC post and the MSG is not DC-qualified.

<b>Is billet in a DC post?</b>	<b>Is MSG DC-qualified?</b>	$v_{g,b}^{DC}$
No	No	0
	Yes	0
Yes	No	1
	Yes	0

Table A.9: Definition of the penalty  $v_{g,b}^{SSgt}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the billet is requesting an A/ and MSG is not A/-qualified.

<b>Is billet requesting SSgt select?</b>	<b>Is MSG a SSgt select?</b>	$v_{g,b}^{SSgt}$
No	No	0
	Yes	0
Yes	No	1
	Yes	0

Table A.10: Definition of the penalty  $v_{g,b}^{Rank}$ , for the assignment of MSG  $g$  to billet  $b$ . This penalty is incurred if the billet does not receive a requested MSG rank.

<b>Billet Request</b>	<b>MSG Rank</b>	$v_{g,b}^{Rank}$
E3	E3	0
	E4	0.3
	E5	0.6
	E6	1
E4	E3	0.3
	E4	0
	E5	0.3
	E6	0.6
E5	E3	0.7
	E4	0.3
	E5	0
	E6	0.3
E6	E3	1
	E4	0.6
	E5	0.3
	E6	0
Any	E3	0
	E4	0
	E5	0
	E6	0

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# APPENDIX B:

## SINGLE COMMODITY FORMULATION OF THE BALANCE MODEL

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Model BALMOD is reformulated from a multi-commodity network to a single commodity network flow formulation called SINGCOM. SINGCOM is utilized for easier implementation in the solver used by MSGAT. This solver is described in Section 3.3.5. The derivation of formulation SINGCOM focuses on the second layer of the network in Figure 2.1. This appendix derives an expression for the optimal objective value of the second layer as a function of the solution to the first layer (Craparo 2010). In other words, while the multi-commodity formulation BALMOD optimizes

$$\min(f(\text{ASSIGN}_{g,b}^c) + g(\text{EXSLOT}_{det,e}^c)),$$

formulation SINGCOM optimizes

$$\min(f(\text{ASSIGN}_{g,b}^c) + f'(\text{ASSIGN}_{g,b}^c))$$

where

$f(\text{ASSIGN}_{g,b}^c)$  denotes the penalties from the first layer,  $g(\text{EXSLOT}_{det,e}^c)$  denotes the penalties from the second layer,  $f'(\text{ASSIGN}_{g,b}^c)$  denotes the optimal penalties from the second layer as a function of the assignment made in the first layer. This appendix derives  $f'(\text{ASSIGN}_{g,b}^c)$ .

### **B.1 Derivation of the Balance Constraints**

The experience penalty,  $pen_e^c$  is defined as the penalty of assigning an MSG with experience level  $c$  to an experience slot that requires experience level  $e$ . Model SINGCOM is equivalent to model BALMOD provided the following assumptions hold:

1. The marginal penalty for each additional mismatch between target experience and actual MSG experience is constant. For example, if a detachment has two experience slots available for a 1st Poster poster, then the penalty of assigning a 3rd Poster to each of these experience slots is the same.

2. There is no penalty for assigning an MSG with experience level  $c$  to an experience slot that requires experience level  $e$ , when  $c = e$ . That is,

$$pen_e^c = 0 \forall c = e.$$

3. All penalties are nonnegative. That is,

$$pen_e^c \geq 0 \forall c, e.$$

4. Smaller experience mismatches result in smaller penalties than larger experience mismatches. That is,

$$\begin{aligned} pen_3^1 &\geq pen_2^1 \\ pen_3^1 &\geq pen_3^2 \\ pen_1^3 &\geq pen_1^2 \\ pen_1^3 &\geq pen_2^3 \end{aligned}$$

5. The penalty of assigning a 1st Poster to an experience slot that requires a 3rd Poster is less than the sum of the penalties of assigning a 1st Poster to a slot that needs a 2nd Poster and assigning a 2nd Poster to a slot that requires a 3rd Poster, and likewise for the penalty of assigning a 3rd Poster to an experience slot that requires a 1st Poster. That is,

$$\begin{aligned} pen_1^3 &\leq pen_1^2 + pen_2^3 \\ pen_3^1 &\leq pen_3^2 + pen_2^1. \end{aligned}$$

Recall that the second layer receives its incoming flow from the first layer, as shown in Figure 2.1. Penalties  $pen_e^c$  are placed on the arcs leaving the detachment nodes, where  $c$  is the MSG experience level (the flow commodity), and  $e$  is the target experience level for the destination experience slot. A slight reformulation of the second layer flow optimization problem for a single detachment is illustrated in Figure B.1. In Figure B.1,  $dem_e^{det}$  is the target number of

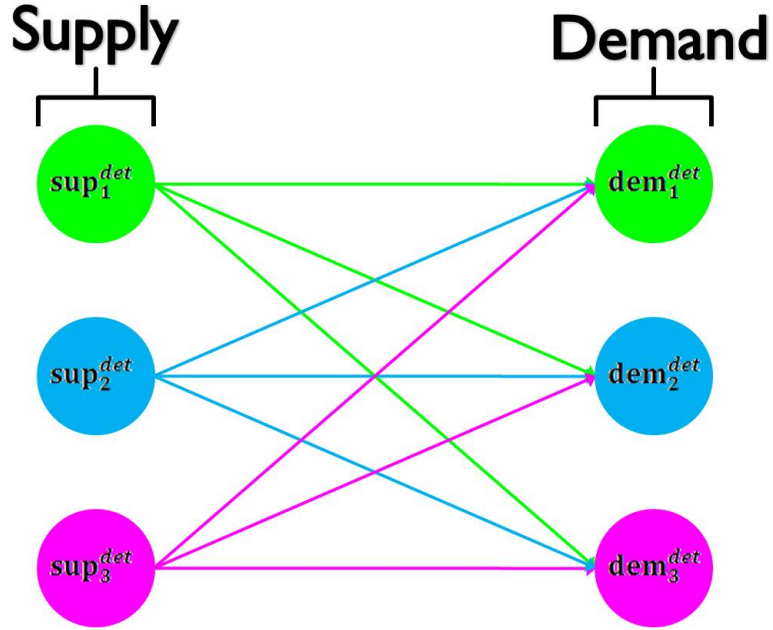


Figure B.1: Reformulation of the second layer flow optimization problem for detachment  $det$ .

MSGs with experience level  $e$  needed at detachment  $det$ , and  $sup_c^{det}$  is the number of MSGs with experience level  $c$  that are assigned to detachment  $det$  in the first layer:

$$sup_c^{det} = \sum_{g,b \in B_{det}} ASSIGN_{g,b}^c \quad \forall c, det. \quad (\text{B.1.1})$$

The arc from supply node  $c$  to demand node  $e$  has cost  $pen_e^c$ . Note that by construction of the detachment demands,

$$sup_1^{det} + sup_2^{det} + sup_3^{det} = dem_1^{det} + dem_2^{det} + dem_3^{det}.$$

Therefore, it is not possible for any detachment to have excess supply or excess demand in the second layer of the network.

### B.1.1 Characterization of Optimal Second Layer Objective Values

Denote the flow from supply node  $c$  to demand node  $e$  for detachment  $det$  as  $X_{c,e}^{det}$ . As a first step in constructing an optimal solution to the network flow problem shown in Figure B.1, the maximum possible amount of flow is pushed horizontally across the network in Figure B.1. In other words,  $X_{c,e}^{det} = \min(sup_c^{det}, dem_e^{det}) \quad \forall c = e$ . This horizontal flow is depicted in Fig-



ure B.2. Since  $pen_e^c = 0 \forall e = c$ , this flow incurs no penalty. Following this initial step, either

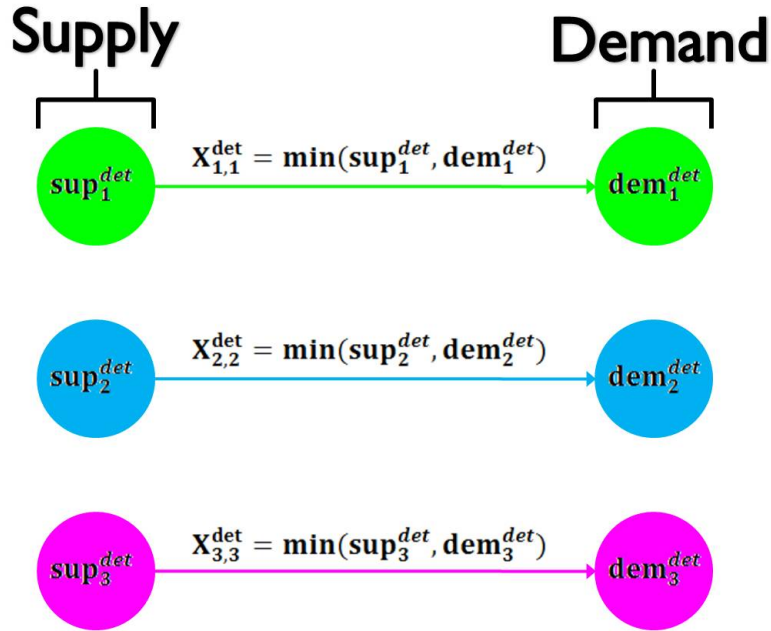


Figure B.2: The maximum amount of flow is pushed across the network from supply node  $e$  to demand node  $e$ .

the supply node, the demand node, or both nodes will be *saturated*. We say that a supply node is saturated if it is unable to supply any additional flow, while a demand node is saturated if it is unable to absorb any additional flow. Note that if the maximum possible volume of flow is pushed directly across the network, then either the supply node for each experience level  $e$  will be unable to supply any additional flow, or the demand node for each experience level  $e$  will be unable to accept any addition flow, or both of these conditions will hold for experience level  $e$ . For simplicity, we assume that exactly one node for each experience level is saturated; a similar procedure can be used to verify that the results of this appendix hold if both nodes are saturated.

Define the *residual network* as the network that remains if all saturated nodes and their associated arcs are removed. Six cases arise for the appearance of the residual network. Table B.1 shows the supply and demand conditions that lead to each of the six cases as well as a schematic diagram of the residual network.

Note that for each of the six cases summarized in Table B.1, only one feasible flow is possible. If only one supply node remains, then all remaining demand must be satisfied by that supply node. Likewise, if only one demand node remains, then all remaining supply must be absorbed by that

demand node. Thus, the objective values for each of these cases can easily be calculated. These objective values are summarized in Table B.2. Note that if both a supply node and a demand node are saturated for a particular experience level, the objective value is correctly calculated by one of the given objective values (Craparo 2010).

To confirm the optimality of the six objective values given in Table B.2, consider the linear program that optimizes the second-layer flow for a given first layer flow:

$$\begin{aligned}
& \min_X (pen_1^1 \cdot X_{1,1} + pen_2^1 \cdot X_{1,2} + pen_3^1 \cdot X_{1,3} + pen_1^2 \cdot X_{2,1} + pen_2^2 \cdot X_{2,2} + \\
& \quad pen_3^2 \cdot X_{2,3} + pen_1^3 \cdot X_{3,1} + pen_2^3 \cdot X_{3,2} + pen_3^3 \cdot X_{3,3}) \\
& s.t. X_{11} + X_{12} + X_{13} = sup_1 \\
& \quad X_{21} + X_{22} + X_{23} = sup_2 \\
& \quad X_{31} + X_{32} + X_{33} = sup_3 \\
& \quad X_{11} + X_{21} + X_{31} = dem_1 \\
& \quad X_{12} + X_{22} + X_{32} = dem_2 \\
& \quad X_{13} + X_{23} + X_{33} = dem_3 \\
& \quad X_{ij} \geq 0 \forall i, j
\end{aligned}$$

For clarity, the *det* index is omitted in the above formulation and in the remainder of the derivation. The dual of this linear program is:

$$\begin{aligned}
& \max(sup_1 \cdot u_1 + sup_2 \cdot u_2 + sup_3 \cdot u_3 + dem_1 \cdot v_1 + dem_2 \cdot v_2 + dem_3 \cdot v_3) \\
& s.t. u_1 + v_1 \leq pen_1^1 \\
& \quad u_1 + v_2 \leq pen_2^1 \\
& \quad u_1 + v_3 \leq pen_3^1 \\
& \quad u_2 + v_1 \leq pen_1^2 \\
& \quad u_2 + v_2 \leq pen_2^2 \\
& \quad u_2 + v_3 \leq pen_3^2 \\
& \quad u_3 + v_1 \leq pen_1^3 \\
& \quad u_3 + v_2 \leq pen_2^3 \\
& \quad u_3 + v_3 \leq pen_3^3
\end{aligned}$$

Since each of the objective values given in Table B.2 results from a feasible solution to the primal problem under the appropriate supply and demand conditions, the optimality of these objective values for each of the six bases can be established via identification of a dual-feasible solution with the same objective value. The following case summary demonstrates the optimality of the objective value for Case 1 by providing such values of  $u_1, u_2, u_3, v_1, v_2,$  and  $v_3$ . One can use a similar procedure to verify that the objective values for Cases 2-6 are optimal.

Table B.1: Six possible supply and demand conditions in the second layer, and the associated residual networks. 1st, 2nd, and 3rd Posters are represented by the green, blue, and pink nodes, respectively. For clarity, the *det* index is omitted.

Case	Conditions	Residual Network
1	$sup_1 \geq dem_1$ $sup_2 \leq dem_2$ $sup_3 \leq dem_3$	
2	$sup_1 \leq dem_1$ $sup_2 \geq dem_2$ $sup_3 \leq dem_3$	
3	$sup_1 \leq dem_1$ $sup_2 \leq dem_2$ $sup_3 \geq dem_3$	
4	$sup_1 \leq dem_1$ $sup_2 \geq dem_2$ $sup_3 \geq dem_3$	
5	$sup_1 \geq dem_1$ $sup_2 \leq dem_2$ $sup_3 \geq dem_3$	
6	$sup_1 \geq dem_1$ $sup_2 \geq dem_2$ $sup_3 \leq dem_3$	

### Case 1

Figure B.3 illustrates the residual network for Case 1, in which the following supply and demand conditions hold:

$$\begin{aligned}
 sup_1 &\geq dem_1 \\
 sup_2 &\leq dem_2 \\
 sup_3 &\leq dem_3.
 \end{aligned}$$

Recall that the objective value given in Table B.2 for Case 1 is

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1$$

A dual feasible solution with the same objective value is:

$$\begin{aligned} u_1 &= 0 & u_2 &= -pen_2^1 & u_3 &= -pen_3^1 \\ v_1 &= 0 & v_2 &= pen_2^1 & v_3 &= pen_3^1 \end{aligned}$$

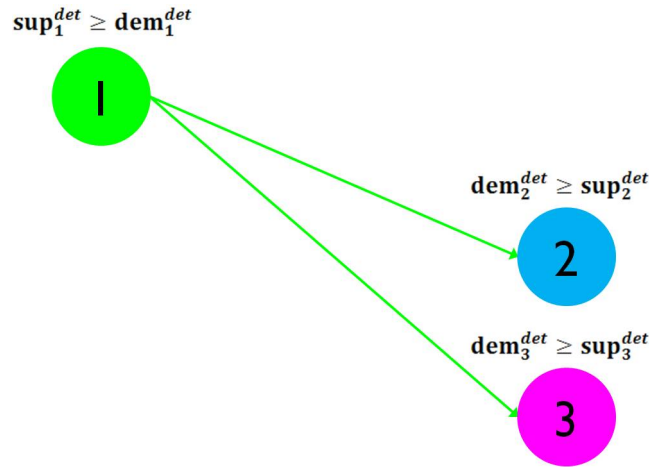


Figure B.3: Residual network when the Case 1 supply and demand conditions are met.

It is easy to verify that this solution satisfies all constraints in the dual formulation above. (To see that the constraint  $u_2 + v_3 \leq pen_3^2$  is satisfied, recall that we have assumed that  $pen_1^3 \leq pen_1^2 + pen_2^3$ .) The objective value of this dual feasible solution is

$$\begin{aligned} & sup_1 \cdot u_1 + sup_2 \cdot u_2 + sup_3 \cdot u_3 + dem_1 \cdot v_1 + dem_2 \cdot v_2 + dem_3 \cdot v_3 \\ &= sup_1 \cdot 0 - sup_2 \cdot pen_2^1 - sup_3 \cdot pen_3^1 + dem_1 \cdot 0 + dem_2 \cdot pen_2^1 + dem_3 \cdot pen_3^1 \\ &= (dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1. \end{aligned}$$

Thus, the objective value given in the first row of Table B.2 is optimal, provided the conditions for Case 1 are met. A similar procedure can be used to verify the optimality of the remaining objective values in Table B.2.

Table B.2: Six possible supply and demand conditions in the second layer, and the resulting objective values. For clarity, the *det* index is omitted.

Case	Conditions	Objective Value
1	$sup_1 \geq dem_1$ $sup_2 \leq dem_2$ $sup_3 \leq dem_3$	$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1$
2	$sup_1 \leq dem_1$ $sup_2 \geq dem_2$ $sup_3 \leq dem_3$	$(dem_1 - sup_1) \cdot pen_1^2 + (dem_3 - sup_3) \cdot pen_3^2$
3	$sup_1 \leq dem_1$ $sup_2 \leq dem_2$ $sup_3 \geq dem_3$	$(dem_1 - sup_1) \cdot pen_1^3 + (dem_2 - sup_2) \cdot pen_2^3$
4	$sup_1 \leq dem_1$ $sup_2 \geq dem_2$ $sup_3 \geq dem_3$	$(sup_2 - dem_2) \cdot pen_1^2 + (sup_3 - dem_3) \cdot pen_1^3$
5	$sup_1 \geq dem_1$ $sup_2 \leq dem_2$ $sup_3 \geq dem_3$	$(sup_1 - dem_1) \cdot pen_2^1 + (sup_3 - dem_3) \cdot pen_2^3$
6	$sup_1 \geq dem_1$ $sup_2 \geq dem_2$ $sup_3 \leq dem_3$	$(sup_1 - dem_1) \cdot pen_3^1 + (sup_2 - dem_2) \cdot pen_3^2$

## B.2 Derivation of Balance Constraints

Having established the optimality of the objective values given in Table B.2 for each of the six possible supply and demand conditions, we now derive a set of linear constraints that ensure that the correct objective value is used, depending on the actual supply and demand conditions encountered in any particular problem instance.

Let  $P_{bal}^{det}$  denote a decision variable that records the balance penalty incurred by detachment *det*, and consider the following system of linear constraints:

$$\begin{aligned}
 P_{bal}^{det} &\geq (dem_2^{det} - sup_2^{det}) \cdot pen_2^1 + (dem_3^{det} - sup_3^{det}) \cdot pen_3^1 \quad \forall det \\
 P_{bal}^{det} &\geq (dem_1^{det} - sup_1^{det}) \cdot pen_1^2 + (dem_3^{det} - sup_3^{det}) \cdot pen_3^2 \quad \forall det \\
 P_{bal}^{det} &\geq (dem_1^{det} - sup_1^{det}) \cdot pen_1^3 + (dem_2^{det} - sup_2^{det}) \cdot pen_2^3 \quad \forall det \\
 P_{bal}^{det} &\geq (sup_2^{det} - dem_2^{det}) \cdot pen_1^2 + (sup_3^{det} - dem_3^{det}) \cdot pen_2^3 \quad \forall det \\
 P_{bal}^{det} &\geq (sup_1^{det} - dem_1^{det}) \cdot pen_2^1 + (sup_3^{det} - dem_3^{det}) \cdot pen_2^3 \quad \forall det
 \end{aligned}$$

$$P_{bal}^{det} \geq (sup_1^{det} - dem_1^{det}) \cdot pen_3^1 + (sup_2^{det} - dem_2^{det}) \cdot pen_3^2 \quad \forall det$$

Denote this system as BALPENCONST. Note that the right hand sides of the constraints in system BALPENCONST are simply the objective values for each of the six cases given in Table B.2. It is straightforward to show that if the supply and demand conditions for Case  $i$  are met at detachment  $det$ , then the constraint whose right hand side is equal to the optimal objective value for Case  $i$  will be active when  $P_{bal}^{det}$  is minimized. In other words, under the supply and demand conditions for Case  $i$ , the objective value for Case  $i$  is the maximum among all the objective values given in Table B.2. As in Section B.1.1, we will prove this property for Case 1 only; it is easy to verify that it holds for the remaining cases.

### Case 1

For clarity, the following derivation omits the index  $det$ . Recall that in Case 1, the following supply and demand conditions hold:

$$\begin{aligned} sup_1 &\geq dem_1 \\ sup_2 &\leq dem_2 \\ sup_3 &\leq dem_3. \end{aligned}$$

The objective value for Case 1 is

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1.$$

We wish to show that the objective value for Case 1 is the maximum among all objective values in Table B.2, provided the supply and demand conditions for Case 1 hold.

First, we wish to show that the optimal objective value for Case 1 is greater than the optimal objective value for Case 2:

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1 \stackrel{?}{\geq} (dem_1 - sup_1) \cdot pen_1^2 + (dem_3 - sup_3) \cdot pen_3^2.$$

Rearranging terms, we have

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot (pen_3^1 - pen_3^2) \stackrel{?}{\geq} (dem_1 - sup_1) \cdot pen_1^2.$$

Recall that we have assumed that Case 1 supply and demand conditions hold, and that  $pen_3^1 \geq pen_3^2$ . Thus, the left hand side of this inequality is nonnegative, while the right hand side is nonpositive. Therefore, the inequality holds.

Next, we wish to show that the optimal objective value for Case 1 is greater than the optimal objective value for Case 3:

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1 \stackrel{?}{\geq} (dem_1 - sup_1) \cdot pen_1^3 + (dem_2 - sup_2) \cdot pen_2^3.$$

Rearranging terms, we have

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1 + (sup_2 - dem_2) \cdot pen_2^3 \stackrel{?}{\geq} (dem_1 - sup_1) \cdot pen_1^3.$$

Recall that we have

$$\begin{aligned} sup_1 + sup_2 + sup_3 &= dem_1 + dem_2 + dem_3 \\ sup_2 - dem_2 &= (dem_1 - sup_1) + (dem_3 - sup_3) \end{aligned}$$

Substituting this expression into the above inequality and rearranging terms, we have

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot (pen_3^1 + pen_2^3) \stackrel{?}{\geq} (dem_1 - sup_1) \cdot (pen_1^3 - pen_2^3)$$

Again, using the fact that Case 1 supply and demand conditions hold, combined with the fact that  $pen_1^3 \geq pen_2^3$ , we can see that the left hand side of this inequality is nonnegative, while the right hand side is nonpositive. Thus, the inequality holds.

Next, we wish to show that the optimal objective value for Case 1 is greater than the optimal objective value for Case 4:

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1 \stackrel{?}{\geq} (sup_2 - dem_2) \cdot pen_1^2 + (sup_3 - dem_3) \cdot pen_1^3.$$

Rearranging terms, we have

$$(dem_2 - sup_2) \cdot (pen_2^1 + pen_1^2) + (dem_3 - sup_3) \cdot (pen_3^1 + pen_1^3) \stackrel{?}{\geq} 0.$$

Because Case 1 supply and demand conditions hold, the left hand side of this inequality is nonnegative. Thus, the inequality holds.

Next, we wish to show that the optimal objective value for Case 1 is greater than the optimal objective value for Case 5:

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1 \stackrel{?}{\geq} (sup_1 - dem_1) \cdot pen_2^1 + (sup_3 - dem_3) \cdot pen_2^3.$$

Rearranging terms, we have

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot (pen_3^1 + pen_2^3) \stackrel{?}{\geq} (sup_1 - dem_1) \cdot pen_2^1.$$

Recall that we have

$$\begin{aligned} sup_1 + sup_2 + sup_3 &= dem_1 + dem_2 + dem_3 \\ sup_1 - dem_1 &= (dem_2 - sup_2) + (dem_3 - sup_3) \end{aligned}$$

Substituting this expression into the above inequality and simplifying, we have

$$\begin{aligned} (dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot (pen_3^1 + pen_2^3) &\stackrel{?}{\geq} (sup_1 - dem_1) \cdot pen_2^1 \\ (dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot (pen_3^1 + pen_2^3) &\stackrel{?}{\geq} ((dem_2 - sup_2) + (dem_3 - sup_3)) \cdot pen_2^1 \\ (dem_3 - sup_3) \cdot (pen_3^1 + pen_2^3) &\stackrel{?}{\geq} (dem_3 - sup_3) \cdot pen_2^1 \\ pen_3^1 + pen_2^3 &\stackrel{?}{\geq} pen_2^1 \end{aligned}$$

Since  $pen_3^1 \geq pen_2^1$  and  $pen_2^3 \geq 0$ , the inequality holds.

Finally, we wish to show that the optimal objective value for Case 1 is greater than the optimal objective value for Case 6:

$$(dem_2 - sup_2) \cdot pen_2^1 + (dem_3 - sup_3) \cdot pen_3^1 \stackrel{?}{\geq} (sup_1 - dem_1) \cdot pen_3^1 + (sup_2 - dem_2) \cdot pen_3^2.$$



Rearranging terms, we have

$$(dem_2 - sup_2) \cdot (pen_2^1 + pen_3^2) + (dem_3 - sup_3) \cdot pen_3^1 \stackrel{?}{\geq} (sup_1 - dem_1) \cdot pen_3^1.$$

Recall that we have

$$\begin{aligned} sup_1 + sup_2 + sup_3 &= dem_1 + dem_2 + dem_3 \\ sup_1 - dem_1 &= (dem_2 - sup_2) + (dem_3 - sup_3) \end{aligned}$$

Substituting this expression into the above inequality and simplifying, we have

$$\begin{aligned} (dem_2 - sup_2) \cdot (pen_2^1 + pen_3^2) + (dem_3 - sup_3) \cdot pen_3^1 &\stackrel{?}{\geq} (sup_1 - dem_1) \cdot pen_3^1 \\ (dem_2 - sup_2) \cdot (pen_2^1 + pen_3^2) + (dem_3 - sup_3) \cdot pen_3^1 &\stackrel{?}{\geq} ((dem_2 - sup_2) + (dem_3 - sup_3)) \cdot pen_3^1 \\ (dem_2 - sup_2) \cdot (pen_2^1 + pen_3^2) &\stackrel{?}{\geq} (dem_2 - sup_2) \cdot pen_3^1 \\ pen_2^1 + pen_3^2 &\stackrel{?}{\geq} pen_3^1 \end{aligned}$$

By our assumption that  $pen_2^1 + pen_3^2 \geq pen_3^1$ , the inequality holds.

This completes the proof of correctness of constraints BALPENCONST under the supply and demand conditions for Case 1. A similar procedure can be used to demonstrate correctness of constraints BALPENCONST for Cases 2-6.

### B.3 Formulation SINGCOM

Section B.2 establishes that the constraints BELPENCONST can be used to calculate the optimal balance penalty for a given assignment of guards to billets. Note that the only decision variables contained in right hand sides of the constraints in BALPENCONST are the supply variables. In particular,

$$sup_c^{det} = \sum_{g,b \in B_{det}} ASSIGN_{g,b}^c \quad \forall c, det. \quad (\text{B.3.1})$$

Thus, BALPENCONST express the optimal penalties from the second layer of formulation BALMOD as a function of the decision variables from the first layer of BALMOD. Note that

the objective values for both layers now consider only total flows from MSGs to billets; thus, it is no longer necessary to distinguish among the three commodities used in BALMOD. Therefore, formulation SINGCOM replaces decision variable  $ASSIGN_{g,b}^c$  with decision variable  $X_{g,b}$ .

### Indices and Sets:

$g \in G$	MSG.
$b \in B$	Billet.
$k \in K$	MSG or billet attribute.
$det \in D$	Detachment.
$e \in \{1, 2, 3\}$	MSG experience level.
$G_e \subseteq G$	Set of MSGs with experience level $e$ .
$B_{det} \subseteq B$	Set of billets located in detachment $det$ .

### Input Data:

$v_{g,b}^k$	Penalty for MSG $g$ , billet $b$ , attribute $k$ .
$w_k$	Weight given to attribute $k$ .
$w_{bal}$	Weight given to the experience balance attribute.
$f_{g,b}$	Force/forbid matrix.
$pen_e^c$	Penalty for satisfying detachment demand for experience level $e$ with an MSG with experience level $c$ .

### Calculated Data:

$cost_{g,b} = \sum_k w_k v_{g,b}^k$	Cost of assigning MSG $g$ to billet $b$ .
$dem_e^{det}$	Number of MSGs with experience level $e$ demanded by detachment $det$ .

### Decision Variables:

$X_{g,b}$	The decision to assign MSG $g$ to billet $b$ .
$P_{bal}^{det}$	The balance penalty incurred for detachment $det$ .

### Formulation: SINGCOM

$$\min_{X, P_{bal}^{det}} \sum_{g,b} cost_{g,b} \cdot X_{g,b} + \sum_{det} w_{bal} \cdot \frac{P_{bal}^{det}}{\max(pen_3^1, pen_1^3) \cdot |B_{det}|}$$

$$s.t. \sum_b X_{g,b} = 1 \quad \forall g \in G \quad (\text{B.3.0})$$

$$\sum_g X_{g,b} = 1 \quad \forall b \in B \quad (\text{B.3.1})$$

$$X_{g,b} \leq f_{g,b} \quad \forall g, b \quad (\text{B.3.2})$$

$$P_{bal}^{det} \geq (dem_2^{det} - \sum_{\substack{g \in G_2 \\ b \in B_{det}}} X_{g,b}) \cdot pen_1^2 + (dem_3^{det} - \sum_{\substack{g \in G_3 \\ b \in B_{det}}} X_{g,b}) \cdot pen_1^3 \quad \forall det \quad (\text{B.3.3})$$

$$P_{bal}^{det} \geq (dem_1^{det} - \sum_{\substack{g \in G_1 \\ b \in B_{det}}} X_{g,b}) \cdot pen_1^2 + (dem_3^{det} - \sum_{\substack{g \in G_3 \\ b \in B_{det}}} X_{g,b}) \cdot pen_2^3 \quad \forall det \quad (\text{B.3.4})$$

$$P_{bal}^{det} \geq (dem_1^{det} - \sum_{\substack{g \in G_1 \\ b \in B_{det}}} X_{g,b}) \cdot pen_1^3 + (dem_2^{det} - \sum_{\substack{g \in G_2 \\ b \in B_{det}}} X_{g,b}) \cdot pen_2^3 \quad \forall det \quad (\text{B.3.5})$$

$$P_{bal}^{det} \geq (\sum_{\substack{g \in G_2 \\ b \in B_{det}}} X_{g,b} - dem_2^{det}) \cdot pen_1^2 + (\sum_{\substack{g \in G_3 \\ b \in B_{det}}} X_{g,b} - dem_3^{det}) \cdot pen_2^3 \quad \forall det \quad (\text{B.3.6})$$

$$P_{bal}^{det} \geq (\sum_{\substack{g \in G_1 \\ b \in B_{det}}} X_{g,b} - dem_1^{det}) \cdot pen_1^2 + (\sum_{\substack{g \in G_3 \\ b \in B_{det}}} X_{g,b} - dem_3^{det}) \cdot pen_2^3 \quad \forall det \quad (\text{B.3.7})$$

$$P_{bal}^{det} \geq (\sum_{\substack{g \in G_1 \\ b \in B_{det}}} X_{g,b} - dem_1^{det}) \cdot pen_1^3 + (\sum_{\substack{g \in G_2 \\ b \in B_{det}}} X_{g,b} - dem_2^{det}) \cdot pen_2^3 \quad \forall det \quad (\text{B.3.8})$$

$$X_{g,b} \in \{0, 1\} \quad \forall g, b \quad (\text{B.3.9})$$

$$P_{bal}^{det} \geq 0 \quad \forall det \quad (\text{B.3.10})$$

SINGCOM's objective function is the same as that of BALMOD. As in formulation BALMOD, a normalization factor is included in the objective function term relating to balance penalty. This is done in order to ensure that the resulting balance penalty is between 0 and 1, as the penalties for the other attributes are. For clarity, formulation SINGCOM assumes that the number of MSGs available is equal to the number of billets available. In reality, this is not always the

case. Thus, MSGAT includes a preprocessing step for handling unequal numbers of MSGs and billets.

### **SINGCOM Constraints**

Constraint B.3.0 ensures that each MSG is assigned to one billet. Constraint B.3.1 ensures that each billet is assigned one MSG. Constraint B.3.2 enforces any constraints the user may have placed on MSG  $g$  and billet  $b$ . Constraints B.3.3 through B.3.8 represent the balance constraints, BALPENCONST. Constraint 2.3.9 indicates that the assignment of MSG  $g$  to billet  $b$  can be either 0 or 1. This constraint is necessary because single commodity network flow problems can have fractional optimal solutions when side constraints such as those in BALPENCONST are present. Fractional optimal solutions have been observed when the LP relaxation of SINGCOM is solved, although empirical results indicate that they are quite rare. Constraint B.3.10 ensures that no detachment incurs a negative balance penalty.

## **B.4 Formulation SCASMOD**

Formulation SCASMOD expands upon formulation SINGCOM. This formulation preserves functionality of formulation SINGCOM and is capable of modifying an existing assignment to meet new constraints while maintaining a user-defined degree of persistence.

### **Indices and Sets:**

$g \in G$	MSG.
$b \in B$	Billet.
$k \in K$	MSG or billet attribute.
$det \in D$	Detachment.
$e \in \{1, 2, 3\}$	MSG experience level.
$G_e \subseteq G$	Set of MSGs with experience level $e$ .
$B_{det} \subseteq B$	Set of billets located in detachment $det$ .

### **Input Data:**

$v_{g,b}^k$	Penalty for MSG $g$ , billet $b$ , attribute $k$ .
$w_k$	Weight given to attribute $k$ .
$w_{bal}$	Weight given to the experience balance attribute.

$f_{g,b}$	The force/forbid matrix.
$pen_e^c$	Penalty for satisfying detachment demand for experience level $e$ with an MSG with experience level $c$ .
$d_{max}$	The maximum number of changes between an old assignment and a new assignment.
$x_{g,b}^{old}$	The matrix of MSG-billet assignments in the assignment being modified.

### Calculated Data:

$cost_{g,b} = \sum_k w_k v_{g,b}^k$	Cost of assigning MSG $g$ to billet $b$ .
$dem_e^{det}$	Number of MSGs with experience level $e$ demanded by detachment $det$ .

### Decision Variables:

$X_{g,b}$	The decision to assign MSG $g$ to billet $b$ .
$P_{bal}^{det}$	The balance penalty incurred for detachment $det$ .
$DIFF_{g,b}$	Indicator variable for recording changes between the new assignment and the old assignment.

### Formulation: SCASMOD

$$\min_{X, P_{bal}^{det}} \sum_{g,b} cost_{g,b} \cdot X_{g,b} + \sum_{det} w_{bal} \cdot \frac{P_{bal}^{det}}{\max(pen_3^1, pen_1^3) \cdot |B_{det}|}$$

$$s.t. \quad \sum_b X_{g,b} = 1 \quad \forall g \in G \quad (\text{B.4.0})$$

$$\sum_g X_{g,b} = 1 \quad \forall b \in B \quad (\text{B.4.1})$$

$$X_{g,b} \leq f_{g,b} \quad \forall g, b \quad (\text{B.4.2})$$

$$P_{bal}^{det} \geq (dem_2^{det} - \sum_{\substack{g \in G_2 \\ b \in B_{det}}} X_{g,b}) \cdot pen_2^1 + (dem_3^{det} - \sum_{\substack{g \in G_3 \\ b \in B_{det}}} X_{g,b}) \cdot pen_3^1 \quad \forall det \quad (\text{B.4.3})$$

$$P_{bal}^{det} \geq (dem_1^{det} - \sum_{\substack{g \in G_1 \\ b \in B_{det}}} X_{g,b}) \cdot pen_1^2 + (dem_3^{det} - \sum_{\substack{g \in G_3 \\ b \in B_{det}}} X_{g,b}) \cdot pen_3^2 \quad \forall det \quad (\text{B.4.4})$$

$$P_{bal}^{det} \geq (dem_1^{det} - \sum_{\substack{g \in G_1 \\ b \in B_{det}}} X_{g,b}) \cdot pen_1^3 + (dem_2^{det} - \sum_{\substack{g \in G_2 \\ b \in B_{det}}} X_{g,b}) \cdot pen_2^3 \quad \forall det \quad (\text{B.4.5})$$

$$P_{bal}^{det} \geq (\sum_{\substack{g \in G_2 \\ b \in B_{det}}} X_{g,b} - dem_2^{det}) \cdot pen_1^2 + (\sum_{\substack{g \in G_3 \\ b \in B_{det}}} X_{g,b}^{det} - dem_3^{det}) \cdot pen_2^3 \quad \forall det \quad (\text{B.4.6})$$

$$P_{bal}^{det} \geq (\sum_{\substack{g \in G_1 \\ b \in B_{det}}} X_{g,b} - dem_1^{det}) \cdot pen_2^1 + (\sum_{\substack{g \in G_3 \\ b \in B_{det}}} X_{g,b} - dem_3^{det}) \cdot pen_2^3 \quad \forall det \quad (\text{B.4.7})$$

$$P_{bal}^{det} \geq (\sum_{\substack{g \in G_1 \\ b \in B_{det}}} X_{g,b} - dem_1^{det}) \cdot pen_3^1 + (\sum_{\substack{g \in G_2 \\ b \in B_{det}}} X_{g,b} - dem_2^{det}) \cdot pen_3^2 \quad \forall det \quad (\text{B.4.8})$$

$$DIFF_{g,b} \geq X_{g,b} - x_{g,b}^{old} \quad \forall g, b \quad (\text{B.4.9})$$

$$DIFF_{g,b} \geq x_{g,b}^{old} - X_{g,b} \quad \forall g, b \quad (\text{B.4.10})$$

$$\sum_{g,b} DIFF_{g,b} \leq 2d_{max} \quad \forall g, b \quad (\text{B.4.11})$$

$$X_{g,b} \in \{0, 1\} \quad \forall g, b \quad (\text{B.4.12})$$

$$P_{bal}^{det}, DIFF \geq 0 \quad \forall g, b \quad (\text{B.4.13})$$

SCASMOD's objective function is the same as that of SINGCOM. Constraint B.4.0 ensures that each guard is assigned to one billet. Constraint B.4.1 ensures that each billet is assigned to one MSG. Constraint B.4.2 illustrates the use of the force/forbid matrix to capture user-defined constraints between MSG  $g$  and billet  $b$  as in formulation SINGCOM. Constraints B.4.3 through B.4.8 represent the balance constraints. Constraints B.4.9 and B.4.10 record the number of changes between the old assignment  $x_{g,b}^{old}$  and the new assignment  $X_{g,b}$ . Constraint B.4.11 ensures that the maximum number of changes is less than the user-defined value  $d_{max}$ . (Note that a change in  $n$  MSG-billet pairs results in a change in  $2n$  entries of  $X_{g,b}$ .) Constraint B.4.12 indicates that decision variable  $X_{g,b}$  is binary. Constraint B.4.13 ensures that decision variables  $P_{bal}^{det}$  and  $DIFF$  are nonnegative.

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