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SOLVING THE ARMY'S CYBER WORKFORCE PLANNING PROBLEM USING STOCHASTIC OPTIMIZATION AND DISCRETE-EVENT SIMULATION MODELING

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ABSTRACT

The U.S. Army Cyber Proponent (Office Chief of Cyber) within the Army's Cyber Center of Excellence is responsible for making many personnel decisions impacting officers in the Army Cyber Branch (ACB). Some of the key leader decisions include how many new cyber officers to hire and/or branch transfer into the ACB each year, and how many cyber officers to promote to the next higher rank (grade) each year. We refer to this decision problem as the Army's Cyber Workforce Planning Problem. We develop and employ a discrete-event simulation model to validate the number of accessions, branch transfers, and promotions (by grade and cyber specialty) prescribed by the optimal solution to a corresponding stochastic goal program that is formulated to meet the demands of the current force structure under conditions of uncertainty in officer retention. In doing so, this research provides effective decision-support to senior cyber leaders and force management technicians.

1 INTRODUCTION

The Army Cyber Branch (ACB) is a basic branch of the United States Army with the mission to plan, synchronize, and conduct cyberspace and electronic warfare operations for the Joint Force (Headquarters, Department of the Army. 2018). The ACB was established in 2014 to support the Department of Defense (DoD) Cyber Mission Force by providing managed career fields for Army cyber officers, warrant officers, and enlisted personnel. These cyber warriors are responsible for operating the DoD information network, along with conducting defensive and offensive cyber operations. The ACB currently has seven managed career fields, which consist of three cyber officer specialties – cyber operations officer (17A), electronic warfare operations officer (17B), and cyberspace tool developer (17D). Optimizing the readiness of the Army's cyber workforce is the top priority of the Army's senior cyber leadership.

The Army Cyber Proponent (Office Chief of Cyber) within the Army's Cyber Center of Excellence at Fort Gordon, GA is responsible for making personnel decisions impacting officers in the ACB. Some of the key leader decisions include how many new cyber officers to access (hire) and/or branch transfer into the ACB each year, and how many cyber officers to promote to the next higher rank (grade) each year. We refer to this decision problem as the Army's Cyber Workforce Planning Problem (CWPP). The ACB manages these cyber officer personnel up to a maximum 30-year career length, making the determination of the optimal number of accessions, branch transfers, and promotions for each cyber specialty challenging. Moreover, the number of authorized cyber personnel positions for each specialty varies depending on the uniqueness of the career field and needs of the Army. These authorized positions (force structure) are codified within the personnel management authorization document (PMAD), a personnel requirements document that underpins the Army's military manpower program.

The rank structure of the ACB includes cyber officers in the ranks of Second Lieutenant through General, but the Army Cyber Proponent (Office Chief of Cyber) is only responsible for managing officers below the rank of Brigadier General, namely Second Lieutenant (2LT), First Lieutenant (1LT), Captain (CPT), Major (MAJ), Lieutenant Colonel (LTC), and Colonel (COL). The pay grades for these ranks are O-1 through O-6, respectively. The Defense Officer Personnel Management Act (DOPMA) of 1980 provides guidance on promotion selection target percentages for the ACB (Rostker, B and Thie, H and Lacy, J and Kawata, J and Purnell, S. 1993). In addition, uncertainty in cyber officer retention rates further complicate the Army's CWPP.

To provide analytical decision-support to the Army Cyber Proponent (Office Chief of Cyber) and help them optimize ACB readiness and manning levels across the Army Cyber enterprise, we develop and employ a discrete-event simulation model to validate the number of accessions, branch transfers, and promotions (by grade and cyber specialty) prescribed by the optimal solution to a corresponding stochastic goal program that is formulated to meet the demands of the current force structure under conditions of uncertainty in officer retention. This pair of models helps senior cyber leaders and force management technicians solve the CWPP.

This paper is structured as follows. In Section 2, we briefly highlight some of the foundational literature in military workforce planning and manpower modeling. In Section 3, we discuss the methodology employed, detailing both the stochastic goal programming and discrete-event simulation models. We provide and discuss the model parameterization and testing results in Section 4, and we conclude in Section 5 with insights and directions for future research.

2 LITERATURE REVIEW

The concise introduction to military workforce planning provided by Bartholomew (2013) and the review of military manpower modeling provided by Gass (1991) serve as a useful starting point to understand the role and importance of manpower systems such as those employed by the military. Earlier works by Price and Piskor (1972) and Martel and Price (1981) applied goal programming and stochastic programming, respectively, to manpower planning. Within recent decades, the transition of the U.S. military to an all-volunteer force in the 1970s provided a wealth of opportunities for operations researchers, and Rostker, B. (2006) provides a detailed history of this research.

Specific to the U.S. Army, Collins et al. (1983) and Hall (2004) describe specific manpower models implemented for workforce planning. Shrimpton and Newman (2005) employs a network optimization to study the allocation of officers into functional areas and reallocation of officers into strategic specialties. Bastian et al. (2017) and Pike et al. (2018) both explore stochastic programming within the medical and aviation specialties. Goal programming addressing officer accessions and career modeling are described by Henry and Ravindran (2005) and Hall and Fu (2015). Bastian et al. (2015) provides stochastic goal programming to address the complexities of workforce planning and manpower modeling in the military medical arena.

3 METHODOLOGY

We first briefly discuss a stochastic goal programming (SGP) model that uses a scenario-based, Monte Carlo simulation approach to solve the Army's CWPP. Next, we describe a discrete-event simulation (DES) model that we use to help validate the optimized SGP solution, followed by a presentation of the model parameters appropriate to our manpower planning system.

3.1 Stochastic Goal Programming Model

We formulate and solve a SGP model to solve the CWPP given stochastic personnel retention rates. Given general uncertainty surrounding personnel retention, we model cyber officer retention rates as random variables from empirically-based but approximated continuous probability distributions using subject-matter expertise from cyber force managers along with knowledge of personnel retention rates from similar specialty Army branches.

We use a scenario-based, Monte Carlo simulation approach (Bastian et al. 2015; Bastian et al. 2017) to approximate the optimal objective function value and solution of the SGP model. Specifically, we stochastically generate $|S|$ scenarios of the CWPP via simultaneous random sampling (with replacement) from the personnel retention probability distributions, from which each scenario corresponds to one realization (i.e., Monte Carlo estimate) of the CWPP. For each CWPP scenario $s \in S$, we solve the respective optimization model to compute the sample optimal objective function value and solution. Thus, we solve the optimal model $|S|$ times with stochastically generated cyber officer retention parameters, and we then approximate the overall optimal objective value and optimal solution to the CWPP by taking the sample average across the S scenarios. The Appendix provides a detailed description of the SGP model formulation sets, parameters, variables, objective function, and goal and hard constraints.

3.2 Discrete-Event Simulation Model

To validate the SGP model discussed above and detailed in the Appendix, we developed a DES model to process cyber officer accessions and branch transferees (i.e., collectively, the number of arrivals) for each cyber area of concentration (AOC) through their (up to) 30-year life cycles. At the beginning of each year, the DES model stochastically determines whether each arrival will be promoted to a higher grade or continue for another year of service at the same grade. At the end of each year, for each AOC, the arrival's current grade (O1-O6) is incremented as appropriate.

At the end of each DES model replication, the model outputs 30 years of data for each AOC, containing replication number, life-cycle year, and number of each grade. The cyber officer promotion rates, number of accessions, and number of branch transferees (entity arrival information) prescribed by the optimal solution to the SGP model are used as inputs to the DES model. The cyber officer retention rates are also used as an empirical distribution in the simulation. The DES model is replicated 50 times using common random number streams for variance reduction.

3.3 Model Parameterization

We first provide some important definitions and explanations of the military human resource terminology that affect how the SGP and DES models are parameterized. An *accession* is the military term for a new hire, which is when an Army officer enters military service. Thus, cyber officers are accessed (hired) into the ACB at the grade (rank) of either O-1 (2LT) or O-2 (1LT); 17As and 17Ds can access as 2LT, and 17As and 17Bs can access as 1LT. A *branch transfer* is the military term for moving an officer from one Army branch to another, which requires approval from the U.S. Army Human Resources Command. At present, Army officers can branch transfer into the ACB at the grade (rank) of O-2 (1LT) or O-3 (CPT); Army officers can branch transfer into 17D as 1LT, and Army officers can branch transfer in 17A, 17B and 17D at CPT. In the military context, *promotion* entails an increase in both military rank and the accompanying pay grade, and it requires the selection from an Army-approved board of senior leaders for more senior ranks. Such board-based promotion decisions are made for cyber officers at the grades (ranks) of O-4 (MAJ), O-5 (LTC), and O-6 (COL). Promotion to O-2 (1LT) and O-3 (CPT) work a bit differently and are all-but-assured, excepting for legal, medical, or personnel issues, so they are not modeled as decision variables within the SGP model presented herein.

Authorizations are officer positions funded by the U.S. Congress to carry out the mission of the U.S. Army. A *documented authorization* is a funded position within an organization that identifies a specific specialty and rank required to meet a stated capability. There are several types of authorizations. The first type is a career field specialty authorization that can be filled only by an officer specifically trained for that job (e.g., cyber operations officer). The second type of documented authorization is an Army immaterial authorization (i.e., hereafter referred to as IMM). Immaterial positions do not require an individual having a specific career specialty. Most immaterial authorizations are executive or leadership positions, such as organizational commanders. The last type of requirement, designated as THS, provides allowances for officers who are neither assigned to nor contributing to the mission of a particular organization. This authorization type includes officers who are students, in transit between assignments, in long-term hospitalization or pending medical discharge, or removed for disciplinary reasons. Table 1 displays authorization data based upon the latest PMAD and provided by the Army Cyber Proponent. For example, there are 464 total 17A authorizations, of which 18 are COL, 53 are LTC, 118 are MAJ, 167 are CPT, 83 are 1LT, and 25 are 2LT.

Table 1: ACB's documented number of authorizations.

	Area of Concentration					
Documented Authorizations	*17A*	*17B*	*17D*	*IMM*	*THS*	**Total**
Total	464	151	123	8	179	925
COL	18	6	2	1	1	28
LTC	53	26	10	2	5	96
MAJ	118	46	30	2	16	212
CPT	167	73	41	3	61	345
1LT	83	0	25	0	96	204
2LT	25	0	15	0	0	40
Company Grade	275	73	81	3	157	589

The *promotion rate* is the number of officers selected for promotion divided by the number of officers considered. The number of officers selected for promotion is a variable in the SGP model, bounded to be within ±10 percent of promotion rates for MAJ, LTC and COL based on DOPMA objectives, when possible. Table 2 displays these rates. For example, the maximum and minimum promotion rates to MAJ for 17A, 17B and 17D are 90% and 70%, respectively. Note that the minimum and maximum values for 1LT and CPT are the same, as these ranks do not follow the DOPMA objectives. The only difference between the minimum and maximum promotion rates for 17A/17D and 17B is that, because 17B cannot access officers as 2LTs, no 17B officers can be promoted to 1LT.

Table 2: minimum and maximum promotion rates based upon DOPMA policy.

	17A / 17D					**17B**				
DOPMA Promotion Rate	*1LT*	*CPT*	*MAJ*	*LTC*	*COL*	*1LT*	*CPT*	*MAJ*	*LTC*	*COL*
Max	0.98	0.95	0.9	0.8	0.6	–	0.95	0.9	0.8	0.6
Min	0.98	0.95	0.7	0.6	0.4	–	0.95	0.7	0.6	0.4

4 RESULTS AND DISCUSSION

In this section, we present and discuss the SGP and DES modeling results. The optimization and simulation solutions and the balance between the two solutions are used in concert to converge upon an implementable solution to the CWPP.

4.1 SGP Modeling Results

Using the model parameters above, we solved the CWPP using the SGP model to identify the optimal number of cyber officer accessions, branch transfers, promotions, structure distribution, and projected inventory. Given the uncertainty in the CWPP is associated with the cyber officer retention rates, we modeled these rates as stochastic parameters, sampled using Monte Carlo simulation. For these parameters, we used normal distributions (representative of similar Army branches) having respective standard deviations of 0.001, 0.005, 0.01, and 0.05, respectively. For each of these standard deviation values, we solved the SGP model for 10, 50, and 100 stochastically-generated scenarios. In the following analysis, we first examine the optimal number of accessions and branch transfers, followed by the optimal number of promotions. Table 3 provides the expected value of the optimal accessions and branch transfers over all scenario and standard deviation combinations.

Table 3: expected values of optimal number of cyber officer accessions/branch transfers.

		17A			**17B**		**17D**		
No. of Scenarios	*Retention SD*	*2LT*	*1LT*	*CPT*	*1LT*	*CPT*	*2LT*	*1LT*	*CPT*
10	0.001	39.5	2.0	0.2	2.6	10.9	15.0	0.0	0.0
	0.005	40.2	1.1	0.6	4.5	8.3	15.0	0.0	0.0
	0.01	38.8	3.8	0.3	3.0	9.4	15.0	0.0	0.0
	0.05	39.3	2.5	1.6	5.0	8.0	15.0	0.0	0.0
50	0.001	39.9	1.7	0.1	4.9	8.2	15.0	0.0	0.0
	0.005	40.2	1.3	0.2	5.0	8.0	15.0	0.0	0.0
	0.01	40.6	0.9	0.4	3.6	9.3	15.0	0.0	0.0
	0.05	39.1	3.4	1.0	1.6	11.7	15.0	0.0	0.0
100	0.001	40.0	1.6	0.2	4.3	8.8	15.0	0.0	0.0
	0.005	39.7	1.9	0.5	4.0	8.8	15.0	0.0	0.0
	0.01	40.1	1.6	0.4	4.0	8.8	15.0	0.0	0.0
	0.05	39.1	3.2	0.9	3.2	10.2	15.0	0.0	0.0

The collective output from solving the SGP model instance variants yields several insights. First, there was not a major difference in the optimal policies for accessions and branch transfers between experiments. In fact, for 17D, the optimal policy was exactly the same for all scenarios, as the number of 2LT accessions equaled its respective structure distribution and documented authorizations (a binding constraint); relaxing this constraint would yield no change because there do not exist any IMM or THS requirements for 2LTs. 17A saw very similar results across most runs, whereas some variation was evident among 17B accessions and branch transfers, albeit with a difference of only 2-3 personnel. These trends indicate that the structure of the ACB largely dictates the optimal number of accessions and branch transfers, and that it is not notably sensitive to reasonable changes in retention rates. Within the context of U.S. Army retention rates, a standard deviation of 0.05 is very high, and we would not expect to see such extreme variation in practice.

The optimal number of promotions the model determined exhibits even less variation than the number of accessions and branch transfers. To wit, the largest difference in the number of promotions between experiments was 0.3 promotions, less than one person. As such, in lieu of listing each experimental result, Table 4 provides the expected values of the optimal promotion rates, which were consistent over all experiments. Note that many of the promotion rates are low when compared with the DOPMA goals; in particular, promotion rates to COL remained at the lower bound for all scenarios.

Table 4: optimal cyber officer promotion rates.

AOC	***1LT***	***CPT***	***MAJ***	***LTC***	***COL***
17A	0.98	0.95	0.82	0.62	0.40
17B	0.98	0.95	0.77	0.71	0.39
17D	0.98	0.95	0.69	0.59	0.39

Finally, we examined the deviations from the objectives. Figure 1 depicts the deviations from each rank-specific manning goal, wherein CG (company grade) entails the aggregate number of 2LTs, 1LTs, and CPTs. Although differences were observed between experiments, we show as a representation of the results the goal-specific deviations for the 0.01 retention rate standard deviation, run over 100 scenarios. The distributions characterized in Figure 1, combined with low promotion rates mentioned above, collectively indicate ACB's current structure has too many authorizations for company grade and MAJ, relative to the number of LTC and COL assignments. Still, the optimal solution resulting in all grades being within 10 officers of their goal is a favorable result considering the constraints of the authorizations, DOPMA promotion rate bounds, and the uncertain nature of the problem.

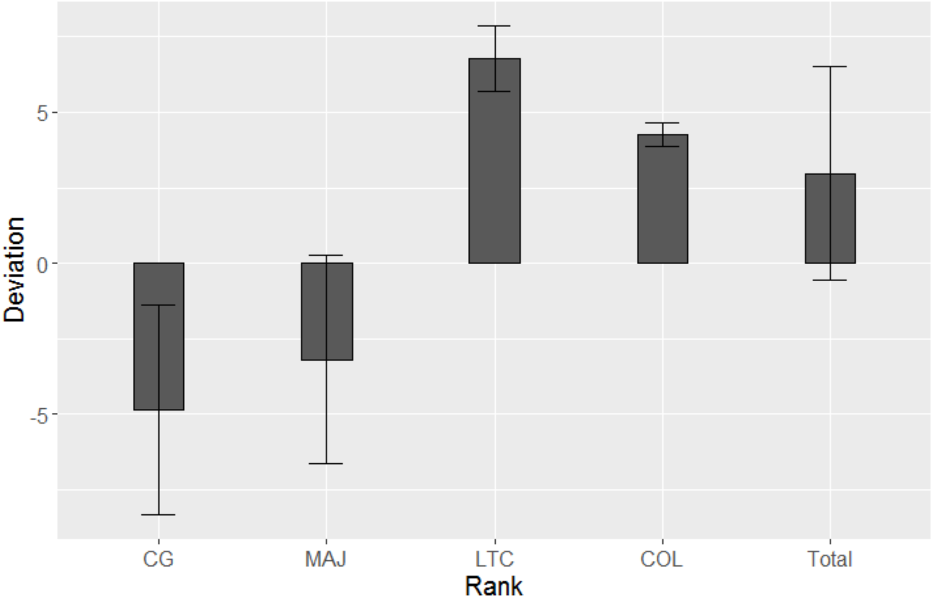

Figure 1: deviations from goal by rank for retention SD of 0.01 with 100 scenarios.

4.2 DES Modeling Results

As inputs to the DES model, we used the optimal number of cyber officer accessions, branch transfers, and promotions prescribed by the SGP model for the case of 100 scenarios with a retention standard deviation of 0.01. We used this case since it accounted for a reasonable amount of uncertainty in retention along with having the most realizations generated in the Monte Carlo simulation. Table 3 provided the entity arrival information for the DES model (i.e., the optimal number of Cyber officer accessions and branch transferees determined by the SGP model), and Table 4 provided the cyber officer promotion rates determined by the SGP model, which are used as the empirical distribution in the DES model.

As a means to validate the SGP model, we used the output of the DES model (coded in ProModel 2018) to create lower-bound and upper-bound limits to the cyber officer total inventory values (summed over the 30-year officer life cycle by grade) for each AOC. We then verified that the optimal values prescribed by the SGP model fell within (or close to) these AOC total inventory limits. Based on the 50 DES model replications, we calculated the average and standard deviation of the total inventory values for each AOC and each grade. Using these values, we computed the 95% confidence interval half-widths to create the lower-bound and upper-bound AOC limits. As previously mentioned, we extracted the optimal values generated by the SGP model. Table 5 shows these results. The first four sub-tables respectively present the average, standard deviation, and (half-width) confidence intervals for the DES. The last sub-table reports the SGP model results.

Table 5: DES and SGP modeling results for the 30-year AOC total inventory limits.

AOC Average from DES Model							
AOC	***2LT***	***1LT***	***CPT***	***MAJ***	***LTC***	***COL***	***Total***
17A	40.74	83.76	225.94	114.92	56.38	18.84	540.58
17B	–	8.06	85.30	53.04	26.32	7.44	180.16
17D	15.20	29.90	81.34	33.80	18.10	4.34	182.68

AOC Standard Deviation from DES Model							
AOC	***2LT***	***1LT***	***CPT***	***MAJ***	***LTC***	***COL***	***Total***
17A	0.90	3.30	16.12	21.22	17.02	13.56	44.93
17B	–	1.00	6.94	13.38	11.21	7.21	26.41
17D	0.64	2.27	10.73	11.79	10.51	4.84	25.51

AOC 95% Confidence (Half-Width) from DES Model							
AOC	***2LT***	***1LT***	***CPT***	***MAJ***	***LTC***	***COL***	***Total***
17A	0.25	0.91	4.47	5.88	4.72	3.76	12.45
17B	–	0.28	1.92	3.71	3.11	2.00	7.32
17D	0.18	0.63	2.97	3.27	2.91	1.34	7.07

AOC Inventory Data from SGP Model							
AOC	***2LT***	***1LT***	***CPT***	***MAJ***	***LTC***	***COL***	***Total***
17A	40.09	84.28	234.85	115.12	58.52	18.54	551.39
17B	–	8.29	84.34	53.69	26.33	8.09	180.74
17D	15.00	30.89	85.78	37.14	18.72	5.76	193.30

To test convergent validity (i.e., model congruence) between the SGP and DES models, we compared the optimization values to the 95% confidence interval (CI) upper- and lower- 30-year AOC total inventory limits. From Table 6, we note the majority of the optimal values computed from the SGP model are within the DES model-based upper and lower bounds, with the exceptions just slightly outside the respective lower- or upper-bounds. For 17A, two of seven are slightly outside of the bounds, above at CPT and below at 2LT. All of the 17B fall within the 95% CI, but six of seven for 17D fall slightly outside of the CI (one slightly below at 2LT and the remainder slightly above). These differences likely result from the limited number of THS and IMM requirements at the junior grades, as well as the general uncertainty in parameterization of the 17D retention probability distributions (i.e., a newly created AOC within the ACB). Upon evaluation of the 99% CI, nearly all optimal values fell within the upper and lower bounds. While future work will further investigate these findings, the overall convergence of the results suggests that the DES model results validate the results of SGP model.

5 CONCLUSIONS

Manpower modeling for a workforce is a critical endeavor to ensure the requisite talent is recruited, promoted, and retained to support the demands of an organizational enterprise. Atypical from most human resource problems, uniformed military workforce planning has a limited number of opportunities and means to recruit new employees, and employees who do not advance in rank are forced out of the organization; these

Table 6: mean estimate / 95% CI for the 30-year AOC total inventory limits.

95% Upper and Lower Limits								
Bounds	***AOC***	***2LT***	***1LT***	***CPT***	***MAJ***	***LTC***	***COL***	***Total***
Upper	**17A**	40.99	84.67	230.41	120.80	61.10	22.60	553.03
Opt Value	–	40.09	84.28	234.85	115.12	58.52	18.54	551.39
Lower	–	40.49	82.85	221.47	109.04	51.66	15.08	528.13
Upper	**17B**	–	8.34	87.22	56.75	29.43	9.44	187.48
Opt Value	–	–	8.29	84.34	53.69	26.33	8.09	180.74
Lower	–	–	7.78	83.38	49.33	23.21	5.44	172.84
Upper	**17D**	15.38	30.53	84.31	37.07	21.01	5.68	189.75
Opt Value	–	15.00	30.89	85.78	37.14	18.72	5.76	193.30
Lower	–	15.02	29.27	78.37	30.53	15.19	3.00	175.61

and other problem characteristics require specialized mathematical models to identify optimal personnel management decisions with respect to recruiting and promotion. Unique to the Army's uniformed cyber workforce is that it is new. Because the ACB was established in 2014, historical data does not exist to accurately inform adaptations of any of the (limited number of) military workforce planning models found in the literature.

This research set forth a SGP model to accurately address the characteristics of military manpower modeling and, more specifically, the Army's uniformed cyber workforce. Given a lack of historical retention data, representative distributions inform unknown model parameters for alternative means of analysis. Using Monte Carlo sampling from the distributions, the expected optimal manpower management decisions are identified over several generated scenarios. The DES model results indicated overall model congruence (i.e., convergent validity at the 95% and 99% CIs) with the SGP model solution.

Foremost among extensions to this research are alternative approaches to address the uncertainty in the parametric retention data, to include strict robust optimization, robust optimization using uncertainty sets, and distributionally robust optimization.

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A APPENDIX

Presented herein are sets, parameters, decision variables necessary to formulate the SGP model, followed by a categorical presentation and discussion of the math programming model's objective function and constraints.

A.1 Sets

G – index for cyber officer grade with $g \in G$
I – index for cyber officer career field (AOC) with $i \in I$
K – index for a cyber officer's year in service with $k \in K$
F – index for each goal with $f \in F$

A.2 Parameters

c_{ig} – documented authorizations for cyber officers in AOC i in grade g
$\tilde{r}_{igk}$ – stochastic retention rate for cyber officers in AOC i in grade g in year k
χ_i – maximum allowable cyber officer structure distribution in AOC i
ρ_i – minimum acceptable cyber officer structure distribution in AOC i
η_{ig} – maximum allowable cyber officer structure distribution in AOC i at grade g
ξ_{ig} – minimum acceptable cyber officer structure distribution in AOC i at grade g
pf_{ig} – minimum cyber officer promotion rate for AOC i at grade g
pc_{ig} – maximum cyber officer promotion rate for AOC i at grade g
IMM_g – Army immaterial authorizations for cyber officers in grade g
THS_g – transients, holdees and students (THS) authorizations for cyber officers in grade g
w_f – decision-maker weight for goal f

A.3 Decision and Goal Deviation Variables

p_{ig} – number of cyber officer promotions for AOC i at grade g, $\forall g = 4,5,6$
a_{ig} – number of cyber officer accessions for AOC i at grade g, $\forall g = 1,2$
b_{ig} – number of cyber officer branch transferees to AOC i at grade g, $\forall g = 2,3$
d_{ig} – cyber officer structure distribution for AOC i in grade g
Inv_{igk} – projected cyber officer inventory for AOC i in grade g in year k
pos_f – positive deviation for goal f
neg_f – negative deviation for goal f

A.4 Objective Function and Constraints

For $s = 1,2,...,S$ solve:

$$\min \quad Z_s = \sum_{f \in F} w_f (pos_f + neg_f) \tag{1}$$

$$\text{subject to} \quad \sum_{g \in G} \left(\sum_{i \in I} (d_{ig} - c_{ig}) - IMM_g - THS_g \right) - pos_1 + neg_1 = 0, \tag{2}$$

$$\sum_{i \in I} (d_{i6} - c_{i6}) - IMM_6 - THS_6 - pos_2 + neg_2 = 0, \tag{3}$$

$$\sum_{i \in I} (d_{i5} - c_{i5}) - IMM_5 - THS_5 - pos_3 + neg_3 = 0, \tag{4}$$

$$\sum_{i \in I} (d_{i4} - c_{i4}) - IMM_4 - THS_4 - pos_4 + neg_4 = 0, \tag{5}$$

$$\sum_{g=1}^{3} \left(\sum_{i \in I} (d_{ig} - c_{ig}) - IMM_g - THS_g \right) - pos_5 + neg_5 = 0. \tag{6}$$

The objective function in (1) of the SGP model seeks to minimize the sum of the weighted goal deviations. The target for the first goal constraint in (2) is for the total cyber officer structure distribution (number of cyber officers) over each grade and AOC to equal the total documented authorizations for cyber officers (over each grade and AOC plus the Army immaterial and THS). The target for the second goal constraint in (3) is for the total cyber officer structure distribution of COLs over each AOC to equal the COL documented authorizations for cyber officers over each AOC plus the Army immaterial and THS. The target for the third goal constraint in (4) is for the total cyber officer structure distribution of LTCs over each AOC to equal the LTC documented authorizations for cyber officers over each AOC plus the Army immaterial and THS. The target for the fourth goal constraint in (5) is for the total cyber officer structure distribution of MAJs over each AOC to equal the MAJ documented authorizations for cyber officers over each AOC plus the Army immaterial and THS. The target for the last goal constraint in (6) is for the total cyber officer structure distribution of Company Grade (sum of 2LT, 1LT and CPT) officers over each AOC to equal the Company Grade documented authorizations for cyber officers over each AOC plus Army immaterial and THS.

$$\sum_{g\in G} d_{ig} \leq \chi_i, \quad \forall\, i \in I, \tag{7}$$

$$\sum_{g\in G} d_{ig} \geq \rho_i, \quad \forall\, i \in I, \tag{8}$$

$$\sum_{g\in G} d_{ig} \geq \sum_{g\in G} c_{ig}, \quad \forall\, i \in I, \tag{9}$$

$$\sum_{g=1}^{3} d_{ig} \geq \sum_{g=1}^{3} c_{ig}, \quad \forall\, i \in I. \tag{10}$$

The constraints in (7) place a maximum allowable cyber officer structure distribution (officer quantity) for each AOC i, whereas the constraints in (8) place a minimum acceptable cyber officer structure distribution for each AOC i (when applicable). The constraints in (9) ensure that the cyber officer structure distribution must meet or exceed the total documented authorizations for cyber officers for each AOC i. The constraints in (10) ensure that the total cyber officer structure distribution for Company Grade (sum of 2LT, 1LT and CPT) officers must meet or exceed the total documented authorizations for Company Grade (sum of 2LT, 1LT and CPT) cyber officers for each AOC i.

$$d_{ig} \geq \xi_{ig}, \quad \forall\, i \in I,\ g \in G, \tag{11}$$

$$d_{ig} \leq \eta_{ig}, \quad \forall\, i \in I,\ g \in G, \tag{12}$$

$$d_{ig} \geq c_{ig}, \quad \forall\, i \in I,\ g \in G. \tag{13}$$

The constraints in (11) require that the cyber officer structure distribution for each AOC i and grade g must meet or exceed the minimum acceptable cyber officer structure distribution for each AOC i and grade g (when applicable). The constraints in (12) ensure that the cyber officer structure distribution for each AOC i and grade g must be less than or equal to the maximum allowable cyber officer structure distribution for each AOC i and grade g (when applicable). The constraints in (13) ensure that the cyber officer structure distribution for each AOC i and grade g must meet or exceed the documented authorizations for cyber officers in each AOC i and grade g.

$$p_{i,4} \geq pf_{i,4} Inv_{i,3,10}, \quad \forall\, i \in I, \tag{14}$$

$$p_{i,5} \geq pf_{i,5} Inv_{i,4,16}, \quad \forall\, i \in I, \tag{15}$$

$$p_{i,6} \geq pf_{i,6} Inv_{i,5,21}, \quad \forall\, i \in I, \tag{16}$$

$$p_{i,4} \leq pc_{i,4} Inv_{i,3,10}, \quad \forall\, i \in I, \tag{17}$$

$$p_{i,5} \leq pc_{i,5} Inv_{i,4,16,} \quad \forall\, i \in I, \tag{18}$$

$$p_{i,6} \leq pc_{i,6} Inv_{i,5,21,} \quad \forall\, i \in I. \tag{19}$$

The constraints in (14) – (16) require the number of resultant Field Grade (MAJ, LTC, COL) cyber officer promotions to be not less than the minimum number of promotions (i.e., the product of the minimum cyber officer promotion rate and inventory) for each respective Field Grade, for each AOC i. Likewise, the constraints in (17) – (19) bound the number of resultant Field Grade (MAJ, LTC, COL) cyber officer promotions to not exceed the maximum number of promotions (i.e., the product of the maximum cyber officer promotion rate and inventory) for each respective Field Grade, for each AOC *i*.

$$d_{ig} = \sum_k Inv_{igk}, \quad \forall\ i \in I, g \in G, \tag{20}$$

$$Inv_{i,1,1} = a_{i,1}\tilde{r}_{i,1,1}, \quad \forall\ i \in \{17A, 17D\}, \tag{21}$$

$$Inv_{i,1,2} = Inv_{i,1,1}(1 - pf_{i,2})\tilde{r}_{i,1,2}, \quad \forall\ i \in \{17A, 17D\}, \tag{22}$$

$$Inv_{i,2,2} = (Inv_{i,1,1}pf_{i,2})\tilde{r}_{i,2,2}, \quad \forall\ i \in \{17A, 17D\}, \tag{23}$$

$$Inv_{i,2,3} = (Inv_{i,2,2} + a_{i,2})\tilde{r}_{i,2,3}, \quad \forall\ i \in \{17A, 17B\}, \tag{24}$$

$$Inv_{17D,2,3} = (Inv_{17D,2,2} + b_{17D,2})\tilde{r}_{17D,2,3}, \tag{25}$$

$$Inv_{i,2,4} = Inv_{i,2,3}(1 - pf_{i,3})\tilde{r}_{i,2,4}, \quad \forall\ i \in I, \tag{26}$$

$$Inv_{i,3,4} = (Inv_{i,2,3}pf_{i,3} + b_{i,3})\tilde{r}_{i,3,4}, \quad \forall\ i \in I, \tag{27}$$

$$Inv_{igk} = Inv_{igk-1}\tilde{r}_{igk}, \quad \forall\ i \in I, g \in G, k \in \{5\text{-}10, 12\text{-}16, 18\text{-}21, 23\text{-}30\}, \tag{28}$$

$$Inv_{i,4,11} = p_{i,4}, \quad \forall\ i \in I \tag{29}$$

$$Inv_{i,3,11} = (Inv_{i,3,10} - p_{i,4})\tilde{r}_{i,3,11}, \quad \forall\ i \in I, \tag{30}$$

$$Inv_{i,5,17} = p_{i,5}, \quad \forall\ i \in I, \tag{31}$$

$$Inv_{i,4,17} = (Inv_{i,4,16} - p_{i,5})\tilde{r}_{i,4,17}, \quad \forall\ i \in I, \tag{32}$$

$$Inv_{i,6,22} = p_{i,6}, \quad \forall\ i \in I, \tag{33}$$

$$Inv_{i,5,22} = (Inv_{i,5,21} - p_{i,6})\tilde{r}_{i,5,22}, \quad \forall\ i \in I. \tag{34}$$

The constraints in (20) assign the cyber officer structure distribution as the total projected cyber officer inventory (over all years) for each AOC *i* and grade *g*. The constraints in (21) - (34) provide the multi-year inventory balance equations, accounting for various grades *g* and each AOC *i*.

$$p_{ig} \geq 0, \quad \forall\ i \in I, g \in \{4, 5, 6\}, \tag{35}$$

$$d_{ig} \geq 0, \quad \forall\ i \in I, g \in G, \tag{36}$$

$$Inv_{igk} \geq 0, \quad \forall\ i \in I, g \in G, k \in K, \tag{37}$$

$$a_{ig} \in \mathbb{Z}_+, \quad \forall\ i \in I, g \in \{1, 2\};\ \text{where } a_{17B,1} = a_{17D,2} = 0, \tag{38}$$

$$b_{ig} \in \mathbb{Z}_+, \quad \forall\ i \in I, g \in \{2, 3\};\ \text{where } b_{17A,2} = b_{17B,2} = 0, \tag{39}$$

$$pos_f, neg_f \geq 0, \quad \forall\ f \in F. \tag{40}$$

The constraints in (35) - (37) represent non-negativity constraints for the promotion, structure distribution, and inventory decision variables. A non-integer solution for these decision variables is an acceptable simplification because of the concept of full-time equivalent employees, which may be fractional; we can augment any fractional requirement along the entire 30-year timeline, as appropriate, during implementation. The constraints in (38) - (39) represent the non-negative, integrality constraints for the accession and branch transfer decision variables, while the constraints in (40) represent the non-negativity constraints for the deviational variables for the set of goals.

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