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A Modeling Framework for Optimizing U.S. Air Force Fighter Pilot Access to Advanced Training Ranges

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Preface

The 2018 National Defense Strategy emphasizes the need for the United States to restore warfighting readiness and field a lethal force capable of defeating aggression by a major power. One element in meeting this goal is enabling units to train in an environment that is sufficiently representative of the threats posed by a major power. For U.S. Air Force (USAF) fighter pilots, this means training at ranges with appropriate airspace, threat emitters, targets, and electronic support measures. Currently, few USAF training ranges have the capabilities to provide fighter pilots with adequate training.

This publication builds on the methodologies and insights from recent RAND Corporation Project AIR FORCE (PAF) analyses that have addressed different aspects of the USAF Strategic Basing Process:

- Sean Bednarz, Anu Narayanan, Paul DeLuca, Joshua Baron, Robert A. Guffey, Daniel M. Romano, and Joseph V. Vesely, *Shaping Domestic Basing Decisions to Ensure Affordable Readiness: A Screening-Level Assessment of Alternative Domestic Basing Postures for the F-35A*, Santa Monica, Calif.: RAND Corporation, 2015, Not available to the general public.
- Anu Narayanan, Sean Bednarz, John A. Ausink, Joshua Baron, Anthony DeCicco, Robert A. Guffey, George E. Hart, John Matsumura, Michael Nixon, Chuck Stelzner, William W. Taylor, and Joseph Vesely, *A Modeling Framework for Optimizing F-35A Strategic Basing Decisions to Meet Training Requirements*, Santa Monica, Calif.: RAND Corporation, RR-1546-AF, 2016.

In fiscal year (FY) 2014, PAF researchers developed a methodology to assess the cost, effectiveness, and risk associated with different basing postures representing various degrees of fleet consolidation and geographic distribution. Using the F-35A as an exemplar, the FY 2014 project showed that moderate consolidation of the F-35A fleet around potential fifth-generation training ranges could save substantial one-time and recurring costs while enabling more aircraft to be based near advanced training ranges capable of supporting fifth-generation fighter training (Bednarz et al., 2015). In that 2015 report, the authors suggested focusing limited range modernization dollars on a

few well-suited training ranges and heavily weighting proximity to these ranges in the basing process for future F-35A operational units.

In FY 2015, PAF developed a modeling framework building on the FY 2014 work, designed to identify basing locations for the F-35A fleet and training range locations that minimize enterprisewide flying costs associated with participation in required combat force training exercises for combat mission-ready pilots (Narayanan et al., 2016).

The USAF is now developing a plan to upgrade some of its existing ranges with capabilities required to provide advanced training (beyond just fifth-generation fighters) and considering potential fighter squadron restationing options that would improve access to upgraded training ranges. The Principal Deputy Assistant Secretary of the Air Force for Installations, Environment and Energy asked PAF to analyze the potential effectiveness of different combinations of range upgrades and squadron restationing. The results of that analysis are documented in unpublished 2020 RAND research from Bradley DeBlois et al. This document provides the technical details of an optimization model that was developed to conduct that analysis.

This research was commissioned by the Principal Deputy Assistant Secretary of the Air Force for Installations, Environment and Energy and conducted within the Resource Management Program of PAF as part of a FY 2019 project entitled *Optimal Basing Posture for U.S.-Based Forces*.

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Acknowledgment of these individuals does not imply their endorsements of the views expressed in this document.

Abbreviations

ANG	Air Force National Guard
AFR	U.S. Air Force Reserve
AFRC	Air Force Reserve Command
FY	fiscal year
MDS	mission design series
MILCON	military construction
PAF	Project AIR FORCE
PuLP	Python Linear Programming
RegAf	Regular Air Force
SUA	special use airspace
USAF	U.S. Air Force

Introduction

Training fighter pilots for combat requires access to training ranges with dedicated airspace and ground capabilities to enable actual or simulated weapons delivery and air-to-air and air-to-ground tactics. These training ranges should include capabilities, such as threat emitters and adversaries, that sufficiently represent the type of threat that aircrews would face in combat.

The U.S. Air Force (USAF) manages a set of 30-plus training ranges that fighter squadrons use daily to conduct required training. However, with the evolution of potential adversary capabilities and the fielding of fifth-generation aircraft, like the F-35A, the existing range enterprise does not provide sufficient capability for required training. Recognizing this shortfall in capability, the USAF is developing a range modernization plan in which some number of the training ranges will be upgraded with the capabilities required to provide adequate training. Fighter squadrons at bases located near these upgraded training ranges would then be able to conduct proper training. However, if not all ranges are upgraded, there will be some number of fighter squadrons without access to adequate training. The USAF is also considering strategic basing actions that would restation fighter squadrons to bases close to upgraded ranges.

This raises issues that RAND Corporation Project AIR FORCE (PAF) researchers have analyzed in recent years. In fiscal year (FY) 2014, PAF researchers developed a methodology to assess the cost, effectiveness, and risk associated with different basing postures representing different degrees of fleet consolidation and geographic distribution (Bednarz et al., 2015). In FY 2015, PAF researchers developed a modeling framework building on the FY 2014 work, designed to identify basing locations for the F-35A fleet and training range locations that minimize enterprise-wide flying costs associated with participation in required combat force training exercises for combat mission-ready pilots (Narayanan et al., 2016).

In FY 2019, the Principal Deputy Assistant Secretary of the Air Force for Installations, Environment and Energy asked PAF researchers to analyze potential squadron restationing options that improve the access of fighter squadrons to the upgraded training ranges to best leverage proximity, capacity, and throughput capability at the

advanced ranges. This tool details the model developed by PAF researchers to produce combinations of range upgrades and squadron moves that maximize effectiveness.¹

Model Overview

The Optimal Basing Tool is a multiobjective optimization model written in Python. The goal of the model is to suggest squadron restationing options for U.S.-based active-duty, Air National Guard (ANG), and USAF Reserve (AFR) squadrons that will increase access to advanced, upgraded training ranges.² Given a list of upgraded ranges and the initial laydown of squadrons with their bases and training range assignments, the model moves squadrons to new locations and reassigns their training ranges to produce an optimal final laydown. The *optimal* laydown is the one in which the squadron assignments to bases and ranges best satisfy the model's objectives. These include maximizing the number of squadrons with access to upgraded ranges and minimizing infrastructure investment, the number of squadron moves, and the distance between a squadron's base and range assignments.

Model inputs represent possible policy choices for the USAF when determining how to increase access to advanced ranges. The number of ranges and which specific ranges to upgrade serve as one set of policy options and can be adjusted with model inputs. Several squadron restationing policies are also represented through a series of inputs that include the number of squadron moves allowed, the capacity constraint of receiving bases, whether different aircraft types can be assigned to the same base, and whether ANG units can be restationed.

The primary output of the model is the set of squadron movements that maximize access to upgraded ranges.³ The model is used to see how the recommended squadron moves change as a function of the policy options, as represented by model inputs. A discussion of the types of analysis the model can support is in Chapter Four.

¹ A separate report summarizes specific findings and recommendations based on the utilization of this model in unpublished 2020 research from Bradley DeBlois, Patrick H. Mills, Anu Narayanan, Dara Gold, Anna Jean Wirth, John Ausink, Bart Bennett, Ronald G. McGarvey, Rahim Ali, James Syme, and Russell H. Williams.

² A squadron has access to a training range if the great circle flying distance from the squadron's basing location to the nearest boundary point of that range is less than or equal to a distance specified by the user. We refer to this distance as the *range_access_distance*, which is described further in the "Model Settings" section in Chapter Two.

³ The model has initial functionality to also optimize which ranges to upgrade. Although this option is available within the model, it is not built out for user access at this point.

Assumptions and Limitations

We made several simplifying assumptions in formulating the choices of base and range assignments and range upgrades as an optimization problem. These include the following:

- The model does not consider sortie requirements or mission design series (MDS)–specific training guidelines when assigning squadrons to training ranges. A higher-fidelity model might only allow squadrons to train at ranges with MDS-specific training infrastructure and/or split a squadron’s assignment across multiple ranges where advanced techniques are trained at upgraded ranges and non-upgraded ranges are used for basic tactics. However, in this model, each squadron can only be assigned to one range.
- The model does not distinguish between training range levels beyond “upgraded” or “not upgraded.” A higher-fidelity model might differentiate between various upgrade levels, which would likely influence the types of squadrons that would need to gain access to them. The model also does not consider special use airspace (SUA), which can be used independent of ground-based training ranges.
- Other aspects of the optimal basing problem that the model does not address include airspace restrictions at training ranges; environmental threats to bases and ranges that could, in practice, affect assignment choices; supply chain interruptions for training ranges; additional costs incurred by housing multiple MDS types at the same base; and personnel considerations, such as training.

Organization of This Document

The primary purpose of this tool is to provide a technical description of the Optimal Basing Tool, not to document any specific analysis or recommendations. However, we do provide a discussion for potential applications of the model.

Chapter Two includes an overview of the model structure and a discussion of its inputs, main optimization code, and outputs. Chapter Three provides the mathematical formulation of the model. Chapter Four provides a discussion of potential model applications. Research that used this model is documented in unpublished RAND research. The Appendix includes details on the model’s input, optimization code, and output files.

Modeling Framework Description

This chapter provides an overview of the Optimal Basing Tool, including its main inputs and outputs. The goal of the model is to find optimal base and range assignments for U.S.-based Regular Air Force (RegAF), AFR, and ANG squadrons. The model is also equipped to find optimal training range upgrades. Because such recommendations must balance squadron priority, movement restrictions, and cost considerations the problem lends itself to a multi-objective optimization framework.

The solution space that the model searches over consists of those laydowns that abide by model constraints (i.e., follow base capacity limits) and squadron-placement eligibility criteria (i.e., a squadron can only be placed at bases that can host its MDS type). Within this solution space, the model searches for one that maximizes squadrons' access to upgraded ranges and minimizes the amount of infrastructure investment required,¹ squadron moves, and the distance between a squadron's base and range assignments.

Model Structure

The Optimal Basing Tool has three main components: (1) inputs, (2) optimization code, and (3) outputs.

Schematically, the components are connected as shown in Figure 2.1.

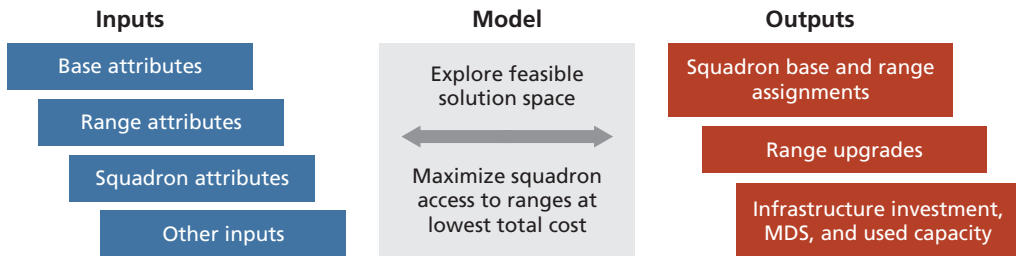
We describe each of the three model components in this section (we provide more detail of the model's file structure in the Appendix).

Inputs

There are three main entities that the model considers when finding an optimal solution: squadrons, ranges, and bases. Data describing their features are critical model

¹ Here, *infrastructure investment* refers to the total cost of all infrastructure needed to add a squadron to a base. This includes but is not limited to military construction (MILCON).

Figure 2.1
Optimal Basing Tool Structure Overview



NOTE: We include range upgrades as an output in this figure because the model can be used to optimize which ranges are upgraded. However, in the current version of the model, this is not a readily accessible user option. A later model iteration can integrate this feature with the other model settings.

inputs. The model also uses cost inputs so it can assign a total cost associated with a new output laydown. Additionally, the user can choose model settings that together with input data, define the parameters of a model run. These inputs and settings are described in this section, with additional details including relevant model files listed in the Appendix.

Input Data

Input data describe the model's core entities: squadrons, air-to-ground ranges, and bases. Although input data can be changed, such information is typically not altered for each model run, because it describes fundamental features of the model's entities.

Squadrons

Squadrons are the foundational organizational unit for the USAF and generally consist of personnel and accompanying equipment. This analysis focuses on flying squadrons of fighter aircraft.² The final placement of squadrons at bases and their range assignments are the primary outputs of this optimization model.

Several characteristics of the squadrons are critical for the rules governing which squadrons can move, where (i.e., to which bases) they can move, which ranges they can be assigned to, and the benefit, if any, of moving a specific squadron. The key squadron input data and their role played in the optimization are described as follows:

- **Component:** A squadron's component indicates whether it is assigned to the RegAF, AFR, or ANG. The component of a squadron has implications for squadron movement. For example, it may be infeasible to move an ANG unit to non-ANG base.

² A model user can also include *squadron equivalents*, or other units that may fall outside the strict definition of a squadron, but that still require base capacity and access to ranges.

- **MDS:** A squadron's MDS is the type of aircraft that a squadron flies. The MDS of a squadron determines where that squadron can be based and whether two squadrons can be colocated with each other.
- **Current base and current range:** The current base and current range of each squadron are specified in the squadron input data. Depending on the level of the current range and the distance of the squadron to that range, there may be a benefit in moving that squadron to a new location.
- **Aggressor:** Aggressor squadrons are manned with experienced fighter pilots who are expressly trained in enemy tactics, weapons, and employment and can provide adversary air support to enable live training for regular fighter squadrons. Because aggressor squadrons are providing training support at specific ranges, an aggressor squadron is typically locked at its starting base, which is chosen by the user to support a particular range and counts toward that base's capacity but not toward range capacity.
- **Weight:** Squadrons are assigned a weight between 0 and 1, with higher weights indicating a higher priority for being near an upgraded range. For example, fifth-generation aircraft, such as the F-35A, have training requirements that can only be met at upgraded ranges. The factors that determine a squadron's weight can include its MDS, mission-tasking, and any other factor that influences its assignment to an upgraded range. Because squadron weights are a user input, they can be informed by whatever factors the user deems relevant. In the first optimization's objective function, a higher objective score is obtained when higher-weight squadrons are within the *range_access_distance* of an upgraded range.

Ranges

Ranges are where squadrons can conduct training exercises. Some ranges are upgraded or are planned to be upgraded, which means that squadrons have (or will have) technological capabilities that can meet the training requirements of fifth-generation (e.g., F-22 and F-35A) fighter platforms. The closer that a squadron is located to a range, the less time it spends in transit and the greater the time it has available to conduct training. The goal of the first optimization is to maximize the number of squadrons that are within close proximity of an upgraded range, which can be achieved by moving squadrons to bases that are close to upgraded ranges and then assigning squadrons to those ranges.³ The key range input data and their role played in the optimization are described as follows:

³ The model does not consider SUA, which can be used independent of ground-based training ranges. This is because the model only evaluates ranges that could potentially be upgraded. Although SUA can be used for certain training exercises, the squadrons in this model could not be exclusively assigned to SUA as their primary training location.

- **Distance to bases:** The distance from a given range to each base is included as a model input.
- **Range capacity:** Range capacity is the maximum number of squadrons that can be assigned to that range.

Bases

Bases are where squadrons are permanently located. Determining the optimum placement of squadrons at bases such that the most squadrons are located close to upgraded ranges is the principle goal of the optimization. To this end, several characteristics of bases play a role in which and how many squadrons can be placed there. The key base input data and their role played in the optimization are described as follows:

- **Location:** The location of a base is specified to determine its distance from ranges.
- **Capacity:** Capacity is the number of squadrons that can be located at a base without additional infrastructure investment. Maximum capacity—which includes the current capacity plus up to two additional squadrons—is also specified. Some model settings, as described in the next section, influence that capacity.
- **Owner:** The owner of the base is the component that base belongs to. The component of a base determines which squadrons can be moved there.
- **MDS:** The MDS of a base is the series currently assigned there. Depending on MDS-mixing rules—a model setting—the current MDS of a base may restrict which squadrons can be moved there.

Costs

The model takes three types of cost inputs. When the model outputs optimal base and range assignments, it also outputs the resulting total costs from adopting these assignments.

- **Range upgrade cost:** The upgrade cost for a range is the investment required for an upgrade.
- **Infrastructure investment costs:** This includes all infrastructure costs of adding squadron capacity to a base beyond its current capacity. This includes military construction (MILCON). Also included are the costs associated with swapping an existing squadron at a base with a new squadron. These costs could be incurred if, for example, fifth-generation aircraft replace fourth-generation aircraft, requiring upgraded maintenance facilities at a base.

- **Squadron displacement costs:** This is the cost of moving a squadron’s personnel and equipment from one base to another in restationing.⁴

Model Settings

In addition to the input data, model settings complete the parameters for a model run. Model settings (also referred to as “levers”) are those values that are expected to change at the beginning of each run. They typically describe policies or excursions that can be tested in a single run. Model settings include the following:

- **Ranges to upgrade:** The user can choose which ranges to upgrade in advance of the model run. The model’s outputs should be interpreted as the optimal squadron assignments, given this choice of range upgrades.
- **Base and squadron lockdowns:** The user can specify squadrons that will stay fixed at their starting bases or bases at which no squadrons will move in or out.
- **Group locking:** This setting allows for all squadrons of a particular component to be locked at their starting bases.
- **Guard swapping:** This setting allows ANG units to only be moved to ANG-designated bases.
- **Range_access_distance:** If a base is within this distance from a training range, squadrons at that base have access to the range. Once chosen as a model setting, it is constant across all base and range pairings. It is in units of nautical miles.

Additional levers and more details are in the Appendix.

Optimization Code

The Python model uses Python Linear Programming (PuLP), open-source software that has a standardized set of commands with which to define a linear optimization problem (Python Package Index, 2020). PuLP is equipped to use a variety of external solvers all within its standardized front-end setup. The Optimal Basing Tool uses the Computational Infrastructure (COIN) Branch and Cut solver from the COIN for Operations Research.

Specifically, the model takes in static inputs and additional model settings to structure the model run. During the run, the model uses four objectives to search the space of feasible solutions and produce an optimal result. An optimal result is one that best satisfies the model’s objectives of

⁴ The costs of investing in infrastructure, moving a squadron between bases, and upgrading a range are in the model’s various data input files (specified in the Appendix).

- maximizing the number of prioritized squadrons assigned to bases within the *range_access_distance* of upgraded ranges, in which the more important squadrons are determined via user-provided weights
- minimizing infrastructure investment
- minimizing the number of squadron moves
- minimizing the sum of distances between squadrons' assigned bases and their assigned ranges.

A solution consists of final base and range assignments for each squadron. If the model is set to also choose training range upgrades and/or an MDS designation for each base, the solution will also specify those factors. See Chapter Three for details on the model's mathematical formulation.

Outputs

As described earlier, the Optimal Basing Tool's main goal is to suggest squadron base and range assignments that maximize access to upgraded training ranges. Reassigning squadrons means that squadrons will move base locations and incur personnel and equipment travel costs, possibly infrastructure investment costs, and range upgrade costs. Base MDS designations, total capacity, and capabilities may change in the process. These output data are stored in the following two files, one that tracks squadron changes and one that tracks base changes:

- **Final Laydown file:** This contains a starting and an ending base assignment, a starting and an ending range assignment, weight, component, and other defining features for each squadron.
- **Final Base Composition file:** This contains base location and capacity, the number and type of squadron that entered or left the base during the run, infrastructure investment costs incurred at the base, and total used capacity

When a batch of runs is conducted (during which the number of range upgrades and move limits are incrementally changed) an additional Batch Summary output file is produced that contains summary information from each run in the batch.

For more details on the content of Output files, see the Appendix.

Technical Model Description

This chapter describes the mathematical formulation of the Optimal Basing Tool. The model has four optimization steps in a tiered structure. It is referred to as a *hierarchy* because the solution space is winnowed in the order of optimization priorities: For the first objective function, solutions that have the best score are first identified; of those, solutions with the best score are found for the second objective function, and so on. The hierarchy and each tier’s mathematical formulation are described next.

Optimization Hierarchy

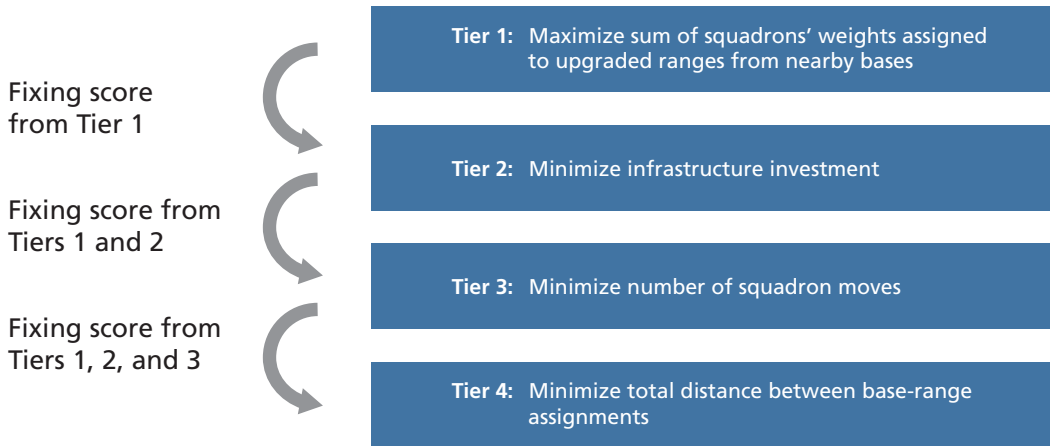
The Optimal Basing Tool finds an optimal set of base and range squadron assignments by considering four objectives: (1) maximizing the sum of squadron weights that have access (and are assigned) to upgraded ranges,¹ (2) minimizing infrastructure investment costs,² (3) minimizing total squadron moves (while remaining below the move cap for the run), and (4) minimizing the total distance between squadrons’ assigned bases and their assigned ranges. The model incorporates these objectives in a tiered structure, using the best objective function score from one tier as a constraint in the next.³ The tiers are ordered by objective priority: Only solutions that best satisfy the first model objective are candidates for the model’s final output. Of those, the solutions are winnowed to those that best satisfy the second objective, and so on. The objectives for each tier are shown in Figure 3.1. See the “Mathematical Formulation” section later in this chapter for the details of each tier.

¹ Squadron weights are user defined in the SquadronData.csv input file (see Table A.1 in the Appendix).

² In the current model, infrastructure investment can take place at active-duty bases. This amounts to extra capacity for up to two squadrons at active-duty bases depending on the *base_capacity* setting for the run (see Table A.2 in the Appendix). These construction spots are costly and, therefore, the model seeks to minimize them (under the construction cap that results from the total capacity).

³ The objective order can be adjusted internally in the model but not by a model user. In future model iterations, this can be integrated as a changeable feature.

Figure 3.1
Optimization Hierarchy



Ultimately, we are interested in solutions that achieve the maximum possible effectiveness score, which is the first tier of the optimization. During the development of the optimization model, initial testing determined that there were often many different bed-down postures that were capable of achieving the maximum-possible effectiveness score. To help select between these alternative optimal solutions, the additional optimization stages (those that minimize infrastructure investment, minimize squadron movements and minimize the distance between squadrons' assigned bases and assigned ranges) were added. The second tier, minimizing infrastructure investment, serves to minimize the number of bases that lose a flying squadron (and, therefore, the number of receiving bases that need to invest in infrastructure to accommodate a new squadron), which is a politically difficult decision.⁴ The next tier minimizes the number of squadron moves to achieve the maximum effectiveness. Finally, minimizing the distance to assigned ranges will minimize the transit time to a range and therefore increase the amount of useable range time per training sortie.

Model Constants and Sets

Model constants are derived through a combination of static inputs, user inputs, and lever values. They are used in the mathematical description of the model's tiers next.

⁴ Minimizing infrastructure investment is not a direct cost constraint (although it has that effect) but is meant to help minimize the force structure shifting across the country. Understanding that states gaining or losing a squadron has political implications, if the maximum effectiveness can be achieved without infrastructure investment (i.e., via swaps), then that is preferred.

Model Constants

1. OBC_b = original base capacity at base b (prior to any MILCON construction or infrastructure investment)
2. BC_b = base capacity at base b (including maximum allowable infrastructure investment)
3. RC_r = range capacity at range r
4. W_s = weight of squadron s (determines relative importance of assigning squadron s to an upgraded range)
5. $D_{b,r}$ = distance in nautical miles between base b and range r
6. TS = total squadrons

Model sets are used for efficiency in searching for optimal solutions. For example, instead of considering whether a squadron should be assigned to a base for which it is ineligible, the model only searches among options with allowable squadron-base pairings. Model sets are defined in Table 3.1 and used in the mathematical description of the model's tiers.

Table 3.1
Model Sets

Lever	Value
SQUADRONS	Set of all squadrons
BASES	Set of all bases
RANGES	Set of all ranges
MDS_TYPES	Set of MDS types used in model
B4S	Dictionary that stores all eligible bases for each squadron ^a
GB4S	Dictionary that stores all "good" eligible bases for each squadron (i.e., those that are within the <i>range_access_distance</i> of an upgraded range)
IB4S	Dictionary that stores initial base assignment for each squadron
S4B	Dictionary that is inverse of B4S (squadrons that are eligible for each base)
SMDS	Dictionary that stores squadrons of each MDS type
GR4B	Dictionary that stores "good" ranges for each base (i.e., upgraded ranges within the <i>range_access_distance</i>)
R_option	Dictionary that stores all eligible ranges for given base ^b
B_option	Dictionary that stores all eligible bases for given range (inverse of <i>R_option</i>)

^a Eligibility depends on base-squadron component matching rules. Additionally, if model lever *mids_constraint* = 0, squadron MDS has to match the base MDS pre-set designation.

^b In this model version, every range is eligible to be assigned to squadrons at any base. Model optimization searches for solutions with range assignments close to base assignments.

Model Constraints

Constraints in the Optimal Basing Tool capture restrictions on base and range capacity, MDS designations at bases, move caps, and internal optimization constraints. While there are other model parameters that constrain its results (i.e., base and squadron lockdowns), this list only includes those that appear explicitly in the mathematical formulation. Specifically, they are:

- **Base squadron capacity:** Stored in static input files. Capacity at active-duty USAF bases can be changed via lever settings that represent potential infrastructure investment and MILCON additions.
- **Range squadron capacity:** Stored in static input files.
- **MDS mixing at bases:** Set via lever inputs. User can specify whether each base must host only one MDS type (and whether it is determined via static model inputs or chosen by the model) or multiple MDS types.
- **Movement caps:** Set via lever inputs. User can specify an upper bound on squadron movements for the run. This model can make fewer moves than this cap if there is no additional objective score benefit.
- **Internal optimization constraints:** The best objective function score from one model tier is input as a constraint in each subsequent tier. This ensures that as the model searches the solution space on a new criteria, it is only choosing from among those solutions that best satisfied the previous one.

Mathematical Formulation

The model's constants, sets, and constraints are used in its mathematical formulation or, more specifically, in each of its optimization steps. As described earlier, the model considers four objectives (prioritized by the model's tiered structure): (1) maximize the sum of squadron weights that can access upgraded ranges, (2) minimize infrastructure investment, (3) minimize squadron moves under a move cap, and (4) minimize the distance between a squadron's base and range assignments. Each of the model's four tiers searches the solution space for a solution with the best objective function score, where the solution space has been winnowed from the previous tier. For example, the first tier finds all solutions (subject to the model's constraints) that maximize the sum of squadron weights assigned to upgraded ranges. There will likely be multiple solutions that yield the same objective score. To choose among them, the model's second tier fixes the first tier's best objective function score as a constraint, which limits the second tier's search to only those solutions found by the first tier. The model finds solutions from this set with the best score for the model's second objective function, and so on.

The formulation for each tier is described as follows. Each tier is defined by the following features:

- **Decision variables:** In this model, decision variables are integer valued and usually binary.
- **Objective function:** The linear objective function describes the tier's goal (or means of winnowing the solution space from the previous tier).
- **Constraints:** These are linear constraints, and one of which will be the best objective score from the previous tier.

Tier 1 Formulation

Decision Variables

1. $x_{s,b,r} = 1$ if squadron s is assigned to base b and range r , 0 otherwise.
If $mds_constraint = 2$, we have an additional decision variable:⁵
2. $y_{m,b} = 1$ if base b hosts MDS type m , 0 otherwise.

Objective Function (Maximize Sum of Squadrons' Weights Assigned to Upgraded Ranges from Bases Within the range_access_distance)⁶

$$max_weights = \sum_{s \in SQUADRONS} \sum_{b \in GBAS(s)} \sum_{r \in GRAB(b)} W_s * x_{s,b,r}$$

Constraints

$$\sum_{b \in B4S(s)} x_{s,b} = 1 \forall s \in S \quad (\text{every squadron is assigned to exactly one base})$$

$$\sum_{b \in S4B(b)} x_{s,b} \leq BC_b \quad \forall b \in B \quad (\text{base capacity not exceeded})$$

$$\sum_{b \in B, s \in S4B(b)} x_{s,b,r} \leq RC_r \quad \forall r \in R \quad (\text{range capacity not exceeded})$$

⁵ $mds_constraint$ is a model lever that determines MDS restrictions at each base. See the Appendix for details and lever value definitions.

⁶ The left-hand side of the objective functions in this section refers to whether we want to minimize or maximize the quantity on the right-hand-side; it is also a shorthand term for what the function is minimizing or maximizing. In this case, we want to maximize the weighted sum of squadrons assigned to upgraded ranges.

$$\sum_{\substack{s \in \text{SQUADRONS}, b \in \text{IB4S}(s) \\ r \in \text{RANGES}}} x_{s,b,r} \geq \text{TS} - \text{moveCap} \quad (\text{squadron movements do not exceed cap}).$$

If $\text{mds_constraint} = 2$, we have additional constraints,

$$\sum_{m \in \text{MDS_TYPES}} y_{m,b} \leq 1 \quad \forall b \in B \quad (\text{at most one MDS per base})$$

$$x_{s,b} \leq y_{m,b} \quad \forall m \in \text{MDS_TYPES}, \forall b \in \text{B4S}(s), \forall s \in \text{SMDS}(m)$$

(squadrons of type m can be stationed at base b only if base b hosts MDS type m).

Tier 2 Formulation

Decision Variables

Same as Tier 1 plus additional:

z_b = number of additional squadron spots used at base b , integer valued.

Objective Function (Minimize Number of Additional Squadron Spots [i.e., Infrastructure Investment] Needed at Bases)

$$\text{min_infrastructure} = \sum_{b \in \text{BASES}} z_b$$

Constraints

All from Tier 1 with additional:

$$\sum_{s \in \text{SQUADRONS}} \sum_{b \in \text{GB4S}(s)} \sum_{r \in \text{GR4B}(b)} W_s * x_{s,b,r} = \text{obj 1 score}$$

(Tier 1's objective function set to the output of its optimization)

$$\left(\sum_{s \in \text{S4B}(b), r \in \text{RANGES}} x_{s,b,r} \right) - \text{OBC}_b \leq z_b \quad \forall b \in B$$

(number of squadrons above original base capacity do not exceed additional squadrons added to base).

Tier 3 Formulation

Decision Variables

Same as Tier 2.

Objective Function (Maximize Squadrons That Stay at Their Starting Bases [i.e., Minimize Total Squadron Moves])

$$\text{max_Stays} = \sum_{\substack{s \in \text{SQUADRONS}, b \in \text{IB4S}(s) \\ r \in \text{RANGES}}} x_{s,b,r}$$

Note that this tier is necessary because, although there is a move cap, nothing prevents the model from making unnecessary moves under this cap.

Constraints

All from Tier 2 with additional

$$\sum_{b \in \text{BASES}} z_b = \text{obj 2 score}$$

(Tier 2's objective function set to the output of its optimization).

Tier 4 Formulation

Decision Variables

Same as Tier 3.

Objective Function (Minimize Total Distance Between Base and Range Assignments)

$$\text{min_Distance} = \sum_{\substack{s \in \text{SQUADRONS}, b \in \text{IB4S}(s) \\ r \in \text{RANGES}}} D_{b,r} * x_{s,b,r}$$

Constraints

All from Tier 3 with additional

$$\sum_{\substack{s \in \text{SQUADRONS}, b \in \text{IB4S}(s) \\ r \in \text{RANGES}}} x_{s,b,r} = \text{obj 3 score}$$

(Tier 3's objective function set to the output of its optimization).

Miscellaneous Model Features and Rules

- Some squadrons have MDS type listed as “Any.” These are allowed to collocate with squadrons of any type, even in one MDS-per-base model modes (*mds_constraint* = 0 and *mds_constraint* = 2). We typically use “Any” to designate test and evaluation squadrons, which often have more than one MDS.
- F-35A and F-16 MDSs can colocate, even in one MDS-per-base model modes (additionally, in *mds_constraint* = 0, the model allows an F-35A base to host all F-16s or vice versa).

Potential Applications

The modeling framework presented in this report provides a quantitative approach for formulating and addressing questions of potential interest to the USAF and other actors with an interest in squadron basing and range upgrade decisions. This section presents a set of exemplar questions and provides guidance on how the framework might be used to address them. Many of these questions were studied and documented in unpublished 2020 RAND research from Bradley DeBlois and colleagues.

Implications for Squadron Basing

Assuming that the set of range upgrade investments to be performed has been determined, we consider the following implications.

How can squadron basing decisions be optimized across the existing network of fighter bases?

The USAF has a robust network of fighter bases across the active-duty, ANG, and AFR squadrons. Significant investments have been made across these bases to make them well-suited for fighter operations. However, given variations in range requirements across multiple MDSs, it may be preferable to perform a reassignment of squadrons to bases, giving preference to high-priority squadrons for basing slots located near high-capability ranges. This optimization model was designed to identify such optimal basing assignments and identify the maximum benefit (measured here in terms of priority-weighted squadrons located within the *range_access_distance* of an upgraded range) that can be achieved for any fixed number of squadron relocations.

What current non-fighter USAF bases would be most beneficial for a future transition to hosting fighter squadron(s)?

There are nonfighter bases located near envisioned high-capability ranges. Although significant facility modifications may be necessary to allow these bases to host fighter squadrons (including, potentially, determining new bases for the units currently resident at the nonfighter bases), the benefit in terms of improved training for future fighter squadrons may be sufficiently great to warrant such network redesign. The optimization model could identify which new basing assignments would gener-

ate the maximum benefit, allowing attention to be focused on a subset of promising locations.

Implications for Range Modernization

Assuming that the set of squadron basing assignments has been determined, we consider the following implications.

What is the optimal set of range upgrades to perform, given limited budget for range investment?

If insufficient funds are available to upgrade all ranges, some subset must be identified for upgrade investment. Such a determination would require a detailed understanding of the differential investment required at each range to bring the range to a particular level of capability, which would require additional analysis. However, given such cost investments, the optimization model could be used to identify the portfolio of range investments that maximizes our benefit metric.

Implications for Jointly Determining Squadron Basing and Range Modernization

What is the relative benefit across mixes of squadron basing reassignments and range upgrades?

It seems obvious that better performance could be achieved by strategically orchestrating squadron basing reassignments and range upgrade decisions in an integrated fashion rather than optimizing each set of decisions in isolation. However, the relative marginal benefit of one additional squadron movement versus one additional range upgrade is not intuitive—and also likely varies across the combined decision space. This optimization model can be used to generate a set of trade-off curves, demonstrating the best performance that can be achieved for any allowed combination of squadron moves and range upgrades.

What alternative basing strategies can achieve optimal (or near-optimal) performance?

The models presented in this tool address a limited set of factors. Many other considerations, including aspects that are not well-suited for inclusion in quantitative modeling, will inform basing decisions. This modeling framework can be used to identify alternative solutions that maximize our benefit metric but also satisfy other constraints related to the feasibility of implementation. For instance, if moving squadrons out of a particular base were deemed infeasible for political considerations, such squadrons can be “locked in place” when the model is run. Note that, in such a case, the difference in benefit between the “unconstrained” and “constrained” solutions presents an impression of the “cost” of accommodating such considerations.

Input, Output, and Optimization Code Files

This Appendix contains details of the model's input, output, and optimization code files (see Table A.1) and the settings (see Table A.2).

Table A.1
Optimal Basing Tool Files

File	Type	Content
<i>BaseData.csv</i>	Input	Base name, base name aliases, latitude and longitude, squadron capacity (and capacity if additional squadron and infrastructure investment slots allowed at base), owner, MDS, ^a and infrastructure investment costs at base. ^b
<i>RangeData.csv</i>	Input	Range, squadron capacity, and upgrade cost
<i>SquadronData.csv</i>	Input	Squadron, component, command, MDS, current base assignment, current range assignment, whether aggressor squadron (yes or no), weight (used to prioritize squadrons), and generation (fourth or fifth)
<i>CostData.csv</i>	Input	One-time cost for moving a squadron. Other costs are stored in <i>BaseData.csv</i> and <i>RangeData.csv</i> input files.
<i>BaseRangeMatrix.csv</i>	Input	Distance in nautical miles between every base and range
<i>UserMenu.csv</i>	Model settings	Choose ranges to upgrade and base and squadron lockdown options. If running in batch mode, choose upgrade order in <i>upgrade_order</i> column. ^c
<i>BasingTool.py</i>	Python model file	Body of Optimal Basing Tool code
<i>RunTool.py</i>	Python model file and model settings	Script to execute main code (hit "Run" here). User selects most model settings (see Table A.2 for full details).

Table A.1—Continued

File	Type	Content
<i>FinalLaydown.csv</i>	Output file	All fields in <i>SquadronData.csv</i> with the following additional squadron data from the model run's settings and solution: lockdown status; initially near an upgraded range; initially assigned near upgraded range; ^d destination base; destination latitude and longitude; destination owner; destination MDS; ^e closest range to destination base; distance to closest range; closest range level; closest target range to destination base; distance to closest target range; closest target range level; range assignment; range assignment level; distance to assigned range; whether squadron was moved; summary stats for final laydown, including total moves; value of Tier 1 objective score; total costs; and squadrons assigned to upgraded ranges within the <i>range_access_distance</i> of assigned base
<i>Bases.csv</i>	Output file ^f	All fields in <i>BaseData.csv</i> with the following additional base data from the model run's settings and solution: Used base capacity, capacity used that exceeds original, fourth- and fifth-generation squadron(s) additions and departures, net change in base spots occupied, infrastructure investment for additional squadrons added above original base capacity
<i>BatchSummary.csv</i>	Output file (only when run in batch mode)	Each row contains summary data from one model run in the batch: run number, number of range upgrades, objective start score (Tier 1 score in optimization hierarchy; see "Optimization Hierarchy" section in Chapter Three), objective end score, move cap, number of moves made, number of squadrons assigned to upgraded ranges within the <i>range_access_distance</i> of their final base, movement cost, range upgrade cost, infrastructure investment, total cost, number of uncovered bases, number of squadrons that required infrastructure investment, number of each MDS type assigned to upgraded range within the <i>range_access_distance</i> of final base, number of bases with net gain and net loss of squadrons, status of each solver used during the run ^g

^a MDS base designation relevant only if *mds_constraint* lever is set to 0 (see Table A.2).

^b MILCON costs for a base include the cost of building a fourth-generation slot, a fifth-generation slot, building two fourth-generation slots, building two fifth-generation slots, building a fourth- and fifth-generation slot and swapping a fifth-generation into a fourth-generation slot. In the current model version, MILCON costs are the same at every base.

^c If a base is locked during the run, no squadrons can move into or out of it. If a squadron is locked, it must stay at its initial base for the run.

^d Note that a squadron can be near an upgraded range but not initially assigned to it. These data are needed to compute the objective function prior to the model run.

^e Destination base MDS is only relevant if *mds_constraint* lever is set to 0 or 2 (i.e., when the model is in single MDS mode).

^f When run in batch mode, the model produces two folders: one with a *FinalLaydown*_{*u,m*}.csv file for each run in the batch, where *u* is the upgrade number for the run and *m* is the move cap for the run, and a second folder with a *bases*_{*u,m*}.csv indexed similarly. The batch run also produces a single *BatchSummary.csv* file (all stamped with data and time of the run) in which each row has summary data for one run in the batch.

^g PuLP solvers can result in five statuses by the end of the run time that the user has allowed: (1) not solved (optimal solution may be possible but solver has not found it yet); (2) optimal (optimal solution found); (3) infeasible (no feasible solutions); (4) unbounded (constraints unbounded so no end to search for single solution); or (5) undefined (no optimal solution found but may exist) (Keen, 2016). In our current model version, each of the four optimizations is allowed to run for 15 minutes.

Table A.2
Model Settings

Setting	Value	Meaning
<i>Upgrade_max</i>	Integer [0, total ranges]	When <i>upgrade_max</i> > <i>upgrade_min</i> , a batch of model runs is completed, one for each upgraded range set in the user menu (and additional varying of the squadron move limits) (upgrades are cumulative). For a single run set <i>upgrade_max</i> = <i>upgrade_min</i> (and similarly <i>min_move</i> = <i>max_moves</i> , see below). <i>To do a single run that upgrades 0 ranges, enter in no upgrades into the UserMenu and set upgrade_min = upgrade_max = 0 (along with min_moves = max_moves).</i>
<i>Upgrade_min</i>	Integer [0, total ranges]	See "Upgrade_max" row.
<i>Compute_dist_matrix</i>	0,1	0: reads in <i>BaseRangeMatrix.csv</i> , which stores distance in nm between every base and range; 1: recomputes this matrix and saves to same file.
<i>Mds_constraint</i>	0,1,2	0: one MDS type per base, stored pre-run in <i>BaseData.csv</i> ; 1: free MDS mixing allowed at bases; 2: one MDS type per base, determined by model.
<i>Base_Capacity</i>	0,1,2	0: bases have their original capacity in <i>BaseData.csv</i> ; 1: active-duty bases have +1 capacity; 2: active-duty bases have +2 capacity. ^a
<i>Min_moves</i>	[0, inf)	For each fixed number of range upgrades, the model does one run for each cap on the allowable squadron moves, or <i>moveCap</i> . The <i>moveCap</i> varies from <i>min_moves</i> to <i>max_moves</i> , set in <i>RunTool.py</i> .
<i>Max_moves</i>	[0, inf)	See "Min_moves" row. Set <i>min_moves</i> = <i>max_moves</i> (along with <i>upgrade_min</i> = <i>upgrade_max</i> for a single run).
<i>Group_lock</i>	0,1,2,3	0: no additional group lockdown; 1: active-duty squads locked; 2: Air Force Reserve Command (AFRC) squads locked; 3: ANG squads locked.
<i>Guard_self_move</i>	0,1	0: no change to component mixing rules; ^b 1: new component mixing rules implemented, active-duty squadrons can be at active-duty bases, AFRC squadrons can be at AFRC or active-duty bases and ANG squadrons can be at ANG bases.
<i>Range_access_distance</i>	[0, inf)	Units of nautical miles. If a base and a range are within this distance, squadrons stationed at the base are said to have access to the range.
Ranges to upgrade	0,1	0: range is not upgraded, 1: range is upgraded.
Squadron/base lockdown	0,1	0: squadron or base is not locked, 1: squadron or base is locked (a locked squadron means it must stay at its starting base and a locked base cannot lose original squadrons or gain new squadrons in the model run).

^a For bases that host both RegAF and AFR or RegAF and ANG components, the model allows +1 capacity. Otherwise, ANG and AFR bases do not have additional capacity. This can be changed in the model's *BaseData.csv* input file if desired. *Additional capacity* refers to number of extra squadrons that a base can accommodate with infrastructure investment.

^b Default component mixing rules: Active-duty squadrons can be at active-duty bases; AFRC squadrons can be at AFRC or active-duty bases; and ANG squadrons can be at ANG or active-duty bases.

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The 2018 National Defense Strategy emphasizes the need for the United States to restore warfighting readiness and field a lethal force capable of defeating aggression by a major power. One element of meeting this goal is enabling units to train in an environment that is sufficiently representative of the threats posed by a major power. For U.S. Air Force (USAF) fighter pilots, this means training at ranges with appropriate airspace, threat emitters, targets, and electronic support measures. Currently, few USAF training ranges have the capabilities to provide fighter pilots with adequate training.

The USAF is now developing a plan to upgrade some of its existing ranges with capabilities required to provide advanced training (beyond just fifth-generation fighters) and is considering potential fighter squadron restationing options that would improve access to upgraded training ranges.

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