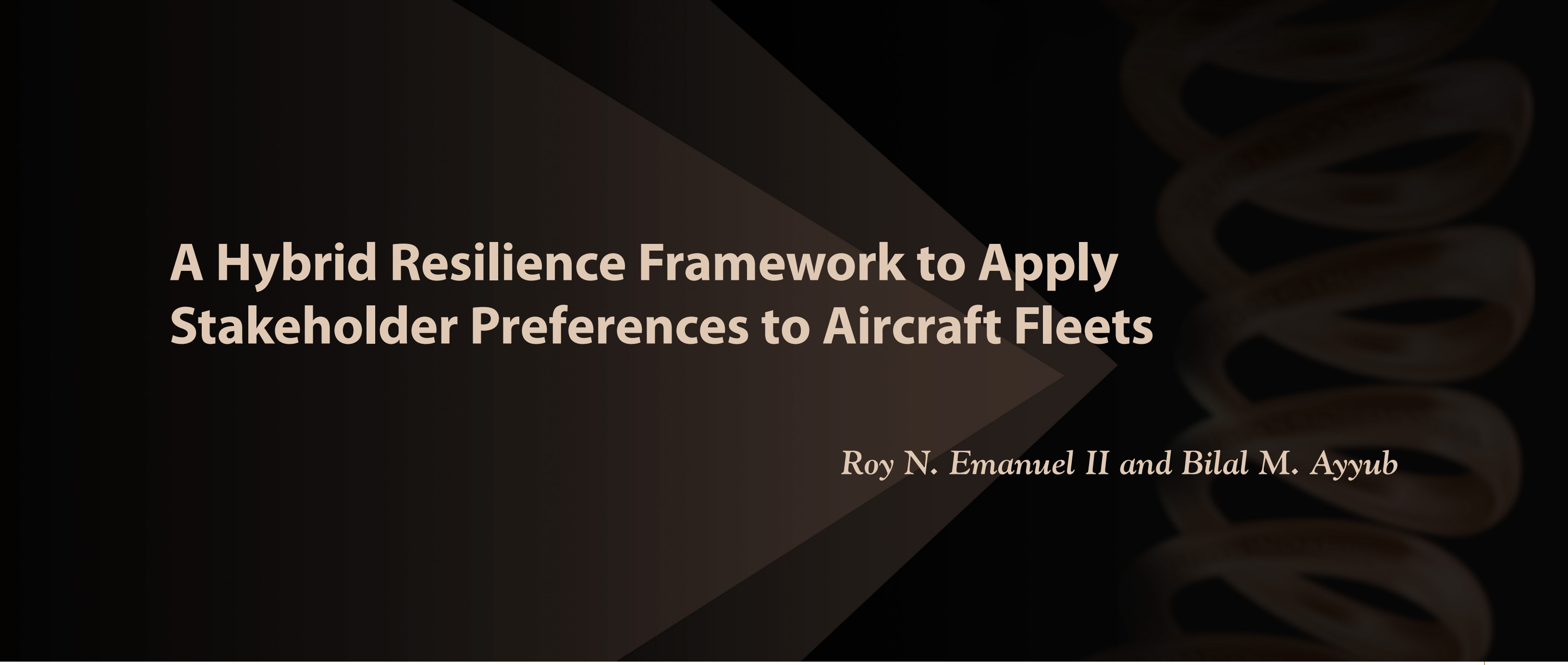


A Hybrid Resilience Framework to Apply Stakeholder Preferences to Aircraft Fleets

Roy N. Emanuel II and Bilal M. Ayyub

ABSTRACT

The U.S. DoD has many complex systems that must remain operationally relevant for decades while satisfying multiple stakeholders with diverse preferences. As these systems reach the end of their service lives, delays in acquiring intended replacement systems drive stakeholders to take action to extend the lives of the aging systems. In the study described in this article, we applied a hybrid resilience framework to a squadron of training aircraft. A discrete event simulation modeled the training squadron's operations over a 35-year period of operations. The simulation provided the time-series functional data input for the resilience analytical model. Key stakeholders in this system are the program manager and the squadron commanding officers. Stakeholder profiles explore different values for time horizon, endogenous need, and intertemporal substitutability. We calculated the resilience of several functional outputs of the training squadron (i.e., graduation rates, satisfaction rates, the number of ready aircraft each day); these calculations allow stakeholders to quantify the impacts of three courses of action.

MOTIVATION

The U.S. DoD manages an incredible number of complicated systems that must operate in austere and unforgiving environments and must be sustained for long periods of time. Through these challenges, DoD must ensure mission success through the fielding, aging, and replacement of these systems. However, difficulties in DoD acquisition often lead to delays in introducing new high-capability systems. Examples of delayed acquisitions include the F-35 Joint Strike Fighter,[1] the *Zumwalt* class of destroyers,[2] the KC-46 tanker aircraft,[3] and U.S. Army command and control systems.[4]

Aging systems must operate beyond their planned lifetimes to compensate for these delays. Such life extension has reliability, safety, and operational implications. One method to deal with the problems of aging systems is a Service Life Extension Program (SLEP), which extends the lifetime of and often adds capabilities to an aging system. Many government systems are undergoing SLEPs, including the Army Tactical Missile System,[5,6] weather radars,[7] ships,[8,9] and aircraft.[10–13]

Resilience modeling and analysis supports critical decisions regarding acquisition and lifetime extension of complex systems. DoD stresses the importance of resilience when defining mission assurance: "a process to protect or ensure the continued function and resilience of capabilities and assets."[14] The current U.S. National Security Strategy prioritizes improving resilience in government functions.[15] It builds on previous presidential policy directives defining the future posture of critical infrastructure systems.[16,17] The operational definition of resilience offered by the Society of Risk Analysis provides a particularly complete framing of the resilience effort in this context:

> Resilience is the ability of a system to reduce the initial adverse effects (absorptive capability) of a disruptive event (stressor) and the time/speed and costs at which it is able to return to an appropriate functionality/equilibrium (adaptive and restorative capability). The disruptive events may be shocking or creeping, endogenous or exogenous.[18]

This definition highlights the critical questions that define the context of the problem—namely, the resilience of what to what. We add an additional contextual factor in this study, the stakeholder (for whom?).

In the study described in this article, we applied a hybrid resilience framework to the problem, leveraging the strengths of both system models and resilience models in the context of a DoD flight training system. We developed a discrete event simulation for the flight operations of a squadron of aircraft; modified a continuous-time resilience model[19,20] to accommodate discrete-time simulations; defined the critical functional outputs of the simulation in accordance with two stakeholders' preferences; and defined stakeholder preference profiles informed by the key functional outputs of the system and threats to mission assurance. Stakeholder preference profiles include time horizon, endogenous preference, and intertemporal substitutability. We quantified the stakeholder-informed resilience of three courses of action for sustaining the squadron of aircraft beyond its planned operational life cycle.

This article consists of five main sections. This first section describes our motivation for studying the problem and applying resilience modeling. The second section describes the resilience framework and the family of models linked to produce a resilience value for a functional output–stakeholder preference profile combination. The third section describes the system of interest, the simulation methodology, and the resilience model. The fourth describes the results of the simulation and the resilience analytical model. The final section provides context for the results by outlining several options for future work, including the system model, stakeholder models, and incorporation of a cost–benefit framework.

HYBRID RESILIENCE FRAMEWORK

The hybrid resilience framework comprises a system simulation, a stakeholder preference model, and a resilience model (see Fig. 1 in Refs. 19–21). Figure 1 depicts the relationships. The hybrid framework guided development of the required functional output data, stakeholder preferences, and the resilience analytical model. The framework connects the outputs of the system of interest or simulation (of what?), the system stressors (to what?), and the desires of different stakeholders (for whom?) to produce a resilience value that can communicate comparative resilience among options for stakeholders who have conflicting and concordant preferences.

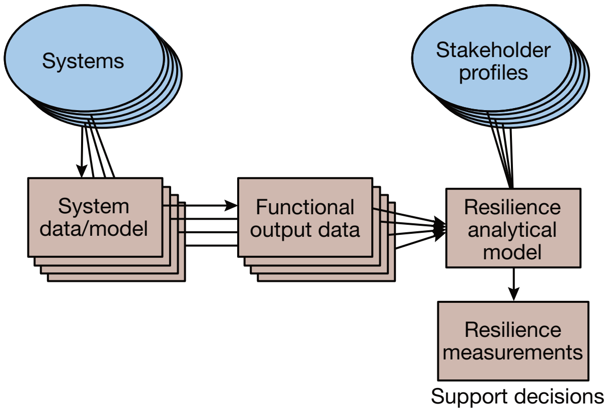


Figure 1. Hybrid resilience framework.

The hybrid resilience framework guides the analyst through the examination of systems and includes the following steps:

1. Identify the system of interest.
2. Identify system representation, for example:
   - System in its operating environment
   - System in a test environment
   - Surrogate system
   - System simulation
3. Collect functional output data, such as:
   - Direct measurement from operating system
   - Direct measurement from test system
   - Outputs from system simulation
4. Define stakeholder preference profiles:
   - Time horizon
   - Endogenous preference
   - Intertemporal substitutability
5. Produce resilience measurements supporting decisions or selection among a set of courses of actions.

System Identification and Functional Output Measurement

The analyst first identifies the system(s) of interest and the functional output(s), thereby setting the scope of the study and driving the physical and functional definitions. Stakeholders require specific outputs from the system of interest. The analyst should always select the system and functional models in this context answering the "of what?" question. The analyst then defines the external layers interfacing with the system of interest.

The external layers provide context for the normal operating environment of the system and the disturbance type, frequency, and magnitude to the system. Defining the threat answers the "to what?" question.[22] The functional performance outputs of the system, φ, are the inputs to the resilience analytical model.[23]

Stakeholder Preference Profiles

The stakeholder preference profiles provide the context for the functional output data, answering the "for whom?" question. Stakeholders must determine the quantity of output that satisfies their needs, the overall time period the system must operate to be useful to them, and the ability to time-shift surplus functional output to periods of shortage.

Endogenous preference, Q, is the amount of the functional output that a stakeholder desires at a given time.[24] Many resilience models assume that the stakeholder's endogenous preference remains constant over time, is equal to the 100% performance level under operating conditions, and does not change after a disturbance.[25] The hybrid resilience framework allows for time- and disturbance-dependent endogenous preferences.[19,20]

Time horizon, t_h, is the farthest time in the future that a stakeholder has interest in an item or process.[24] The concept has a significant impact on the results of a resilience analysis because time horizon changes with a change in stakeholder perspective.[19,20] For example, a squadron commanding officer's primary concern is satisfying production requirements during a 3-year command period. A program manager must consider the entire life cycle of the system. In the environment we are discussing, time horizon depends on the readiness of a replacement system.

Intertemporal substitutability, χ, is the "replacement of the consumption of a good or service at one point in time by consumption at a different time."[24] Intertemporal substitutability takes values from 0 to 1. The value of χ may be constant for the entire time horizon, or it may depend on time or events. Two special values of χ are the ephemeral and permanent cases. The ephemeral case ($\chi = 0$) allows no substitution across time. In the permanent case ($\chi = 1$), a surplus retains its value or utility throughout the time horizon.

Resilience Model

We applied a resilience model that incorporates stakeholder preferences.[19,20,23,25] The resilience model captures the ratio of functional output to desired functional output over the stakeholder's entire time horizon. The resilience model is:

$$R = \frac{M_\chi \Delta T_i + F_\chi \Delta T_f + R_\chi \Delta T_r + H_\chi \Delta T_h}{\Delta T_i + \Delta T_f + \Delta T_r + \Delta T_h}, \qquad (1)$$

where R is resilience and the factors M_χ, F_χ, etc., capture the ratio of actual performance to desired performance. The ΔT factors are segments of time before system failure begins (ΔT_i), from failure initiation to the failure completion (ΔT_f), during recovery (ΔT_r), and post-recovery (ΔT_h). The equations for performance ratios (M_χ, etc.) are:

$$F_\chi(t) = \begin{cases} \dfrac{\int_{t_i}^{t_f} \varphi(t)dt}{\int_{t_i}^{t_f} Q(t)dt} & \text{for } \varphi(t) \le Q(t) \\[2ex] 1 + \chi(t)\dfrac{\int_{t_i}^{t_f} \varphi(t) - Q(t)dt}{\int_{t_i}^{t_f} Q(t)dt} & \text{for } \varphi(t) > Q(t) \end{cases} \qquad (2)$$

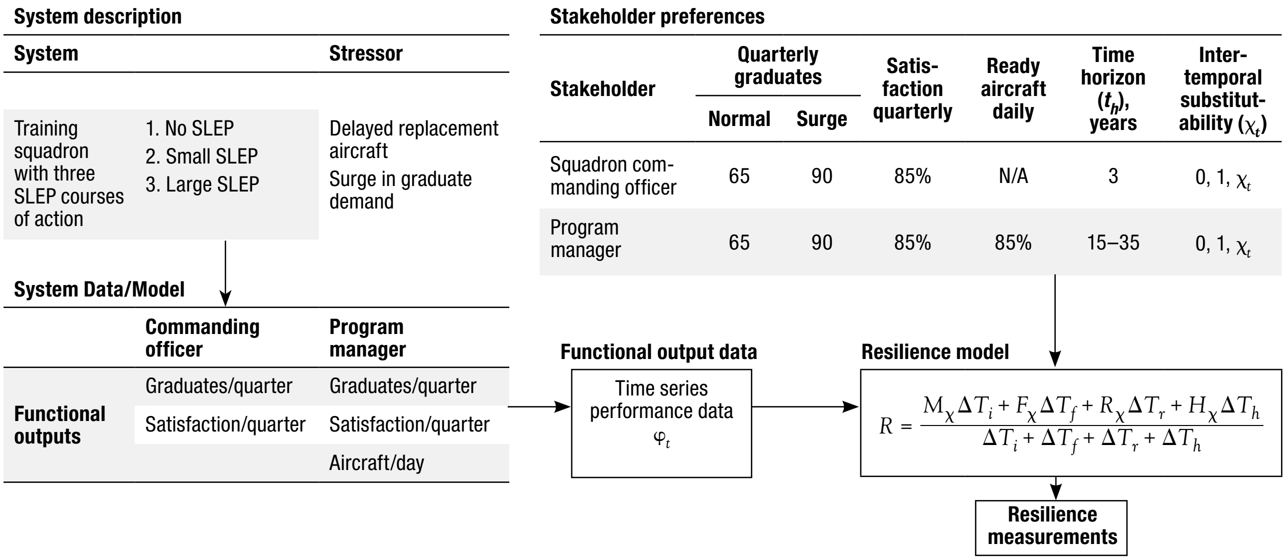
The study represents the operations of a flight training squadron with a discrete event simulation, so a discrete representation of the resilience model is necessary to use the simulation's outputs. Equation 1 remains unchanged, but each profile (Eq. 2) must be modified as follows to accommodate discrete time steps of the simulation:

$$F_{\chi,t} = \begin{cases} \dfrac{\sum_{\tau = t_i}^{t_f} \varphi_\tau}{\sum_{\tau = t_i}^{t_f} Q_\tau} & \text{for } \varphi_t \le Q_t \\[2ex] 1 + \chi_t \dfrac{\sum_{\tau = t_i}^{t_f} \varphi_\tau - Q_\tau}{\sum_{\tau = t_i}^{t_f} Q_\tau} & \text{for } \varphi_t > Q_t \end{cases} \qquad (3)$$

Table 1 describes the parameters in the stakeholder performance profile with their respective symbols and description. Each stakeholder defines their own preference profile including time horizon (t_h), endogenous preference (Q_t), and intertemporal substitutability (χ). The resilience model applies the preference profile to the system performance (φ_t) over time to yield a dimensionless value for resilience.

Table 1. Components of the stakeholder preference profile

Name	Symbol	Description
Time horizon	t_h	The latest time that a stakeholder is interested in system output
Endogenous preference	Q_t	Output desired by stakeholder at time *t*
Intertemporal substitutability	χ	The fraction of surplus output available to satisfy a shortfall



System		Stressor
Training squadron with three SLEP courses of action	1. No SLEP 2. Small SLEP 3. Large SLEP	Delayed replacement aircraft Surge in graduate demand

	Commanding officer	Program manager
Functional outputs	Graduates/quarter	Graduates/quarter
	Satisfaction/quarter	Satisfaction/quarter
		Aircraft/day

Stakeholder	Quarterly graduates		Satisfaction quarterly	Ready aircraft daily	Time horizon (t_h), years	Intertemporal substitutability (χ_t)
	Normal	Surge				
Squadron commanding officer	65	90	85%	N/A	3	0, 1, χ_t
Program manager	65	90	85%	85%	15–35	0, 1, χ_t

$$R = \frac{M_\chi \Delta T_i + F_\chi \Delta T_f + R_\chi \Delta T_r + H_\chi \Delta T_h}{\Delta T_i + \Delta T_f + \Delta T_r + \Delta T_h}$$

Figure 2. Case study hybrid resilience framework. N/A, not applicable.

CASE STUDY: TRAINING SQUADRON OF AIRCRAFT

In the introduction, we noted DoD challenges with aging systems and delayed acquisitions.[26–28] One solution we mentioned, a SLEP, can mitigate a host of problems:

- Parts obsolescence[29]
- Parts deterioration[13]
- Capability improvement[26]

The decisions involving development of a SLEP include which systems to modify, how much life to add, how many systems to include in the SLEP, and when the SLEP should occur. The impacts of these decisions often extend well beyond the career lifetimes of the people who make them. Considering the time horizons of the individuals is important.

This case study is based on current U.S. Navy and U.S. Air Force jet trainers (T-45 Goshawk and T-38 Talon). These aircraft, along with instructor pilots, train pilots to fly advanced tactical aircraft. Trainer aircraft require less maintenance and cost less than tactical aircraft. The T-X aircraft is the oft-delayed replacement for the T-38.[30] No replacement yet exists for the T-45; the T-45 is undergoing a SLEP to increase its operational lifetime. The T-45 SLEP includes detailed inspections, preventive parts replacement, corrosion control, and crack control.[13]

When possible, we used unclassified U.S. Navy documents available via official DoD websites to guide development of the simulation. When information was missing, we made simulation decisions consistent with personal experience and to make the simulation tractable.

Figure 2 depicts the hybrid resilience framework for the training squadron case study. The system of interest is the training squadron comprising aircrew and aircraft. System stressors include delays fielding a replacement aircraft and surges in required graduates produced per quarter. The stakeholders share functional outputs: graduation per quarter and satisfaction rate. Program managers are concerned with these two outputs as well as daily aircraft availability. The stakeholders have different preference profiles (time horizon, endogenous preference, and intertemporal substitutability) for each functional output. The resilience analytical model calculates resilience of each functional output–stakeholder preference pairing.

The next sections discuss the system simulation and resilience analytical framework in detail. The program manager has three courses of action for supporting the aircraft (Table 2): do nothing (no SLEP), increase the operational life to 14,400 flight hours (small SLEP), or increase the operational life to 18,000 flight hours (large SLEP). The program manager must also consider a change in demand for graduates. We investigated the impact of a two-year surge of desired graduates manifested by larger incoming classes and an increase in endogenous need. The average class size increased to 35 per month from a normal size of 25. A uniform distribution for 70–130% of the average class size provides varia-

Table 2. SLEP courses of action

Course of Action	Post-SLEP Lifetime	Time to SLEP (Months)
No SLEP	N/A (7,200)	N/A
Small SLEP	14,400	9
Large SLEP	18,000	12

N/A, Not applicable.

Table 3. Student class sizes

Operations	Minimum Class Size (Per Month)	Maximum Class Size (Per Month)	Desired Graduates (Per Quarter)
Normal	18	32	65
Surge	25	41	90

Table 4. Simulation parameter starting values

Parameter	Value
Aircraft	50
Students	50
Instructors	40
Aircraft lifetime	7200 h
Aircraft SLEP trigger	7000 h

tion in the class size per month. The demand for students increased from 65 students per quarter to 90 students per quarter (see Table 3).

Training Squadron Simulation

The squadron simulation comprises two primary objects: aircrew and aircraft. Multiple processes, defined by a scheduler object, determine which aircraft and aircrew are available at a given time and match the available aircraft and aircrew to conduct a training event. Figure 3 depicts the simulation flow. The simulation revolves around a flight. A flight requires a student, an instructor, and an aircraft. The aircraft components were airframe, propulsion, and avionics. Each component had its own failure rate and repair time. When the flight is completed, each component of the aircraft is either up or down. If a component is down, maintenance personnel repair it and then return the aircraft to the flight status. Each component's expended life is compared with the available life. Instructors give each student a pass or fail grade after each flight. After a certain number of passing flights, the student graduates and is placed in the graduate pool for assignment to a tactical squadron. The system is a fleet of 50 aircraft with a monthly matriculation of 25 students. Matriculation numbers are drawn from a uniform distribution from 18 to 32. The aircraft lifetime is 7200 h (Table 4). Under this normal operating procedure, the aircraft last just until the planned ends of their lives, or 15 years.

The motivating problem is an uncertain time horizon. The study scenario introduces a delay to the procurement and fielding of a follow-on training aircraft. To solve this problem, the program manager initiates a SLEP for the airframe. As each aircraft approaches its life limit, it is placed in a queue to receive modifications to enhance its lifetime. The study looks at extending operational use of the fleet in 5-year increments from 15 years (original lifetime) to 35 years.

The following sections define the simulation entities in more detail.

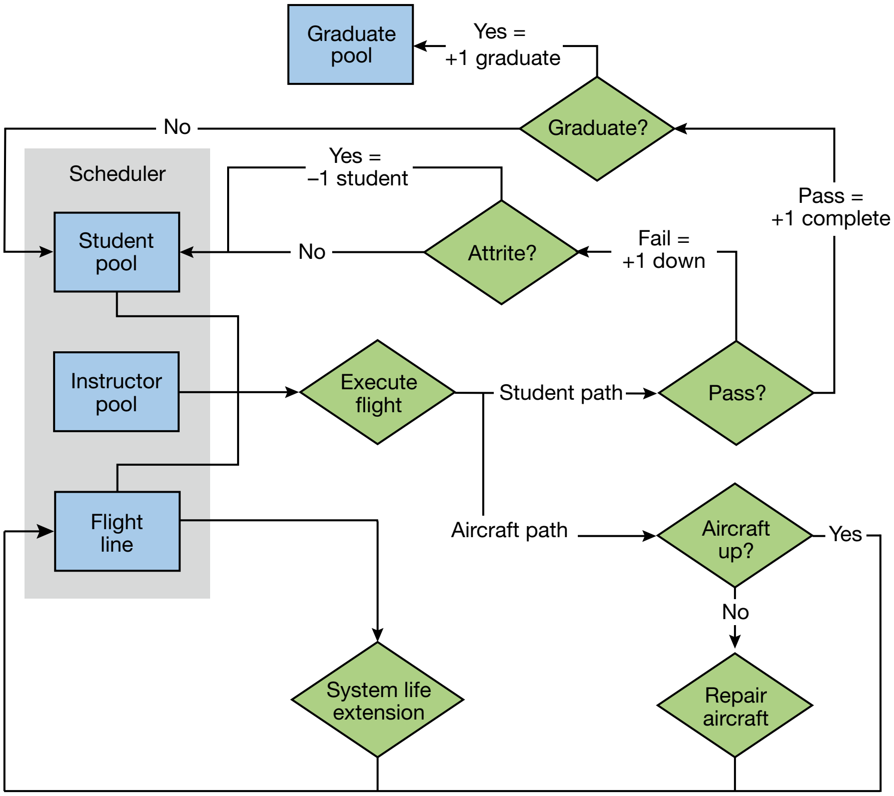


Figure 3. Squadron fleet operation flow of events.

Aircraft Model

An aircraft comprises three parts: airframe, avionics, and propulsion. A part has a lifetime, a repair time, and a failure rate. Part failure rates are dependent only on flight hours. In the simulation, the failure distribution is an exponential distribution with λ set, as depicted in Table 5. Parts must be repaired so that they are as good as new, and the time-to-repair distribution is defined as a lognormal distribution that remains the same throughout time. Further studies could capture the uncertainty of these parameters and their time/use dependence.

Each part (airframe, avionics, and propulsion) has its own failure distribution, repair distribution, SLEP trigger time, lifetime, and lifetime added through SLEP. For this case study, the air-

Table 5. Aircraft simulation values

Part	Characteristic	Value (Hours)
Airframe	Average time to failure	100
	Average time to repair	720
	Fatigue life to trigger SLEP	7000
Propulsion	Average time to failure	40
	Average time to repair	240
Avionics	Average time to failure	30
	Average time to repair	240

Table 6. Model parameter values for aircrew

Parameter	Student Value	Instructor Value
Events per day	2	3
Events in curriculum	61	N/A
Event failure rate	3.5%	N/A
Failed events allowed	3	N/A

N/A, Not applicable.

frame is the part of primary significance, and only the airframe underwent SLEP. As a consequence, the airframe has additional parameters of time to SLEP, additional hours due to SLEP, and age to start SLEP.

Aircrew

Students and instructors are aircrew. A student graduates with 61 complete flights and fewer than 4 failed flights.[31] The student enters the "attrited students" pool after failing 4 flights. Each flight has a 3.5% chance to result in a failure. During 61 graded flights, a student has an 84% chance to graduate. If a part on the aircraft fails during the flight, the flight is graded as incomplete and must be reflown. A student may fly up to two flights per day. The simulation begins with a set amount of students. Every 30 days, a new class of students matriculates into the flight program. Table 6 summarizes the parameters used for the aircrew. Class size can be manipulated to reflect the changing needs of the squadron commander and for sundown of the system. Instructors may fly up to three flights a day.

SLEP Simulation

The program manager faces three different SLEP strategies: no SLEP, small SLEP, and large SLEP. The no-SLEP option adds no life to the aircraft, but it avoids taking aircraft out of the flight schedule for the extended time required to conduct SLEP. Small SLEP increases the lifetime of the aircraft to 14,400 flight hours, but the aircraft will be unavailable for 9 months during the SLEP. Large SLEP increases the lifetime of the aircraft to 18,000 flight hours, but the aircraft will be unavailable for 12 months during the SLEP.

An aircraft enters the SLEP line when it reaches its SLEP flight hour limit. The SLEP line has a limited number of slots available in the hangar, so the program manager gradually introduces aircraft to the SLEP line. The simulation assigns each aircraft a flight limit ranging from 3500 to 7000 flight hours to prevent excessive wait times.

Flight Scheduling

The scheduler is the heartbeat of the squadron simulation. The scheduler's calendar is a 5-day flying week and a 2-day maintenance-only weekend. Each flying day is split into four events spaced by 3 h for each start time. The scheduler uses a uniform distribution to select a flight time between 0.5 and 2.0 h for a single event.

The two disruptive events are fleet deterioration and a change in demand for graduates. Each flight consumes a portion of the acceptable lifetime of each aircraft component. When an aircraft's lifetime is exhausted, it must retire or undergo a SLEP. The alternative courses of action are different options to extend the life of the aircraft. Life extension activities remove aircraft from use to train the flight line for life extension, so aircraft undergoing SLEP are unavailable for flights. While fleet deterioration is a gradual, predictable event, demand for students can fluctuate at any time. The commanding officer must change the daily flight schedule to accommodate these changes.

The scheduler assesses the available aircraft, instructors, and students to make a match for the flights during an event. Aircraft that have surpassed their SLEP flight hours are sent to the SLEP line. Aircraft in the SLEP line wait for a SLEP spot to become available. Once an aircraft is in a SLEP spot, it returns to the flight line after 6 or 9 months, depending on the life added to the system. When aircraft have surpassed their lifetime, they are no longer available for SLEP or the flight schedule. For each event, the scheduler makes student–instructor–aircraft matches until one pool is exhausted. The results of a flight are:

- Student outcomes
  - Incomplete flight due to aircraft failure
  - Passed flight
  - Failed flight
- Aircraft outcomes
  - Down status
  - Up status
  - Send to SLEP line
  - End of life

The scheduler updates all the objects involved in the flight: it adds flight hours to the aircraft and parts; updates student syllabus completion data; assesses student status (graduate, attrite, continuing); adds a new class of students monthly; assesses aircraft repair status

Table 7. Stakeholder preference profiles

Stakeholder	Critical Output	Time Horizon (Years)	Endogenous Preference	Intertemporal Substitutability
Commanding officer	Quarterly graduates	3	Normal (65)/surge (90)	Ephemeral, permanent
	Student satisfaction		85%	Ephemeral
Program manager	Daily availability	15–35	85%	Ephemeral
	Quarterly graduates		Normal (65)/surge (90)	Ephemeral, permanent
	Student satisfaction		85%	Ephemeral

(up or down); assesses aircraft flight line status (flight line, SLEP line, end of life); and assesses the status of aircraft in the SLEP line (waiting, in SLEP, complete).

Stakeholder Profiles

The study includes two stakeholder profiles: squadron commanders and the program manager. Table 7 shows the functional outputs of interest and the associated values for time horizon, endogenous preference, and intertemporal substitutability for each stakeholder.

The program manager is responsible for maintaining the viability of the fleet of aircraft until a replacement system is operational. Viability is assessed daily as the ratio of aircraft ready to provide training events to the total number of aircraft assigned to the squadron. The program manager must also ensure that the flight system produces enough graduates over its lifetime and that students graduate in a reasonable amount of time. The program manager's time horizon is uncertain. The resilience analytical model outputs values at 15, 20, 25, 30, and 35 years of aircraft operations.

The commanding officer has two functional outputs of interest: graduates per quarter and satisfaction rate. The percentage of students graduating under the time limit per quarter is the satisfaction rate. Squadron commanders have a 3-year tenure, so their time horizon, or t_h, is 3 years. Although, in reality, squadron commanders would care about success before and after their tenure, the simulation treats them as singularly focused on their period of command, with no concerns about quota satisfaction before or after that period. A surplus of graduates during one quarter may have value transferable to the previous or following quarter. The study will investigate different types of intertemporal substitutability to include ephemeral and permanent values. Graduate satisfaction rates are ephemeral ($\chi = 0$).

RESULTS

The discrete event simulation produces time-series data for aircraft disposition and status; graduates, attrites, and matriculated students; and time to graduate for each student. Figure 4 shows a single run for each course of action in the surge scenario. The solid line is the number of aircraft on the flight line, the dashed line is the desired number of graduates per quarter, and the points are the actual number of graduates per quarter. The shaded area from 12 to 14 years highlights the 2-year surge in required graduates.

The box plots show the maximum, minimum, and quartiles of the resilience values. The ends of the vertical lines are the maximum and minimum resilience, the top and bottom edges of the box are the 75th and 25th percentiles, and the dark hash is the median resilience.

Program Managers

The program manager applies the preference profiles and desired functional outputs defined in Table 7. A series of three figures presents the resilience results. Each figure shows the results for a single time horizon. This presentation enables the program manger to visually inspect the preferred course of action. Figure 5 shows results for the daily-aircraft-ready-to-fly functional output. Figure 6 shows surge and non-surge results for the graduates-per-quarter output over all time horizons of interest and for the ephemeral and permanent values of χ. Figure 7 shows results for the student satisfaction functional output.

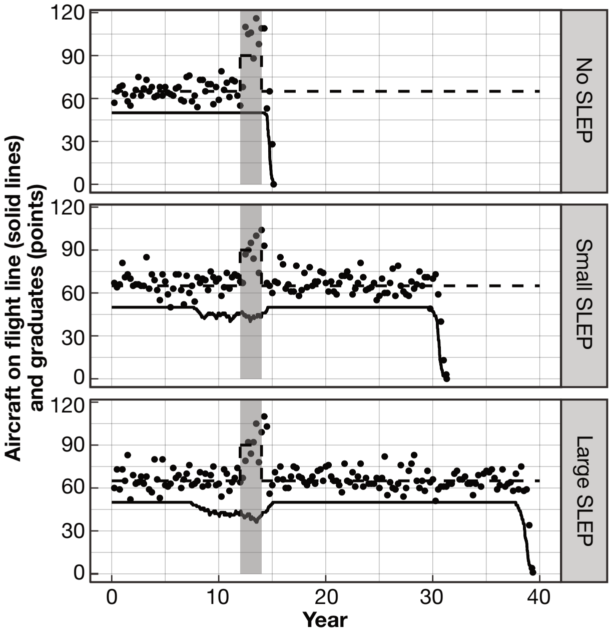


Figure 4. Simulation output example of aircraft data and quarterly graduates for each SLEP option without surge in students.

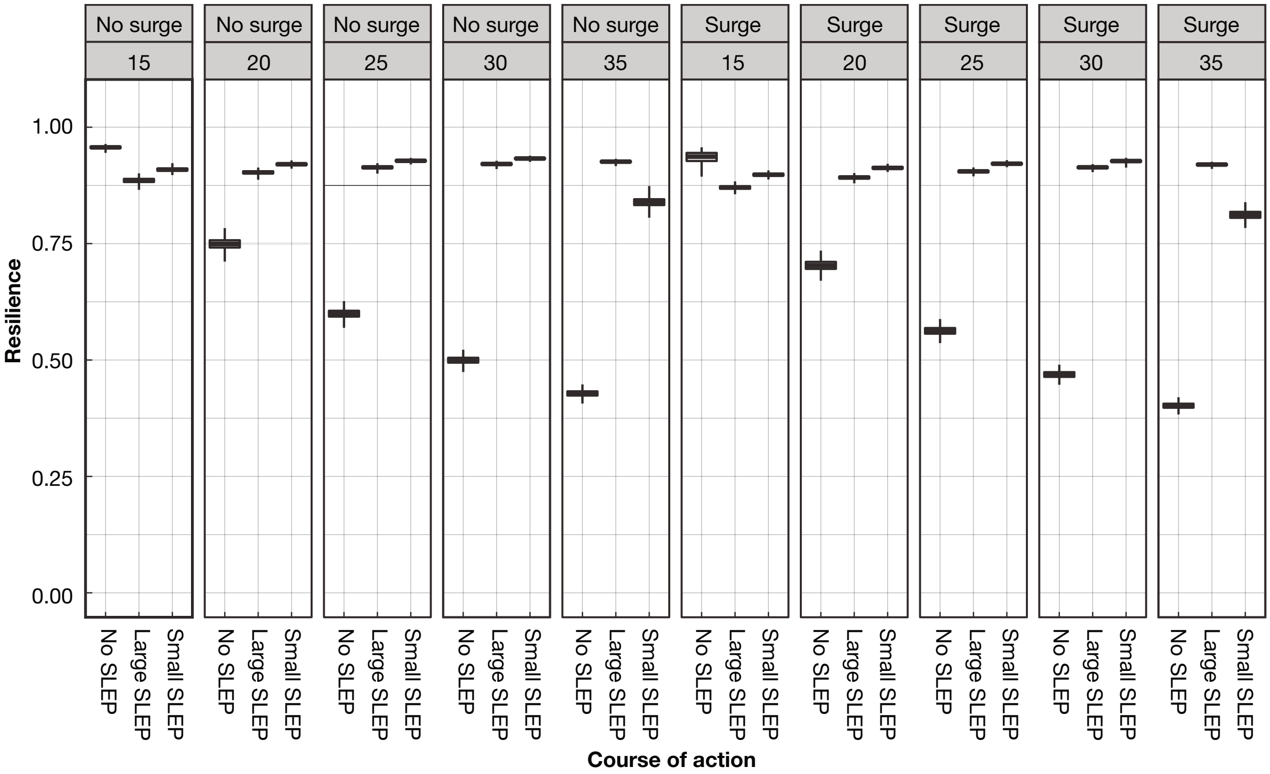


Figure 5. Program manager daily-ready-aircraft resilience results for 15-, 20-, 25-, 30-, and 35-year time horizons with and without a surge in student matriculation.

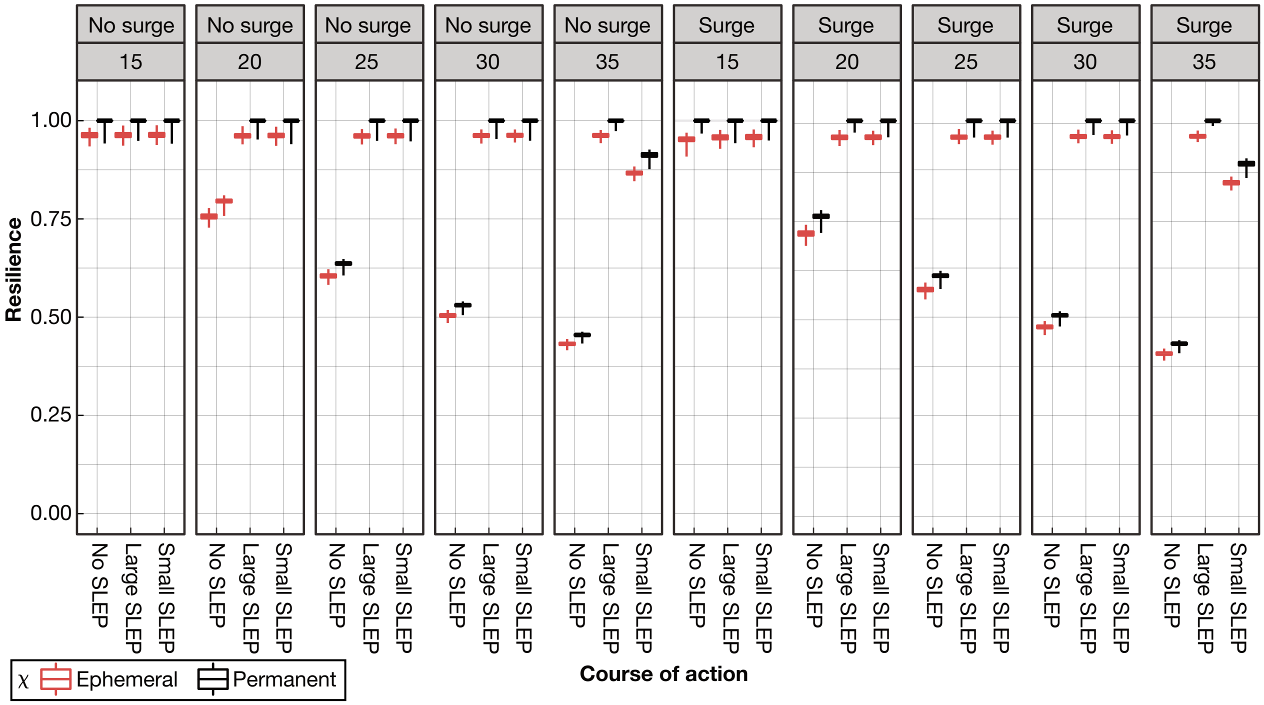


Figure 6. Program manager graduate resilience results for 15-, 20-, 25-, 30-, and 35-year time horizons with and without a surge in student matriculation ephemeral and permanent intertemporal substitutability profiles.

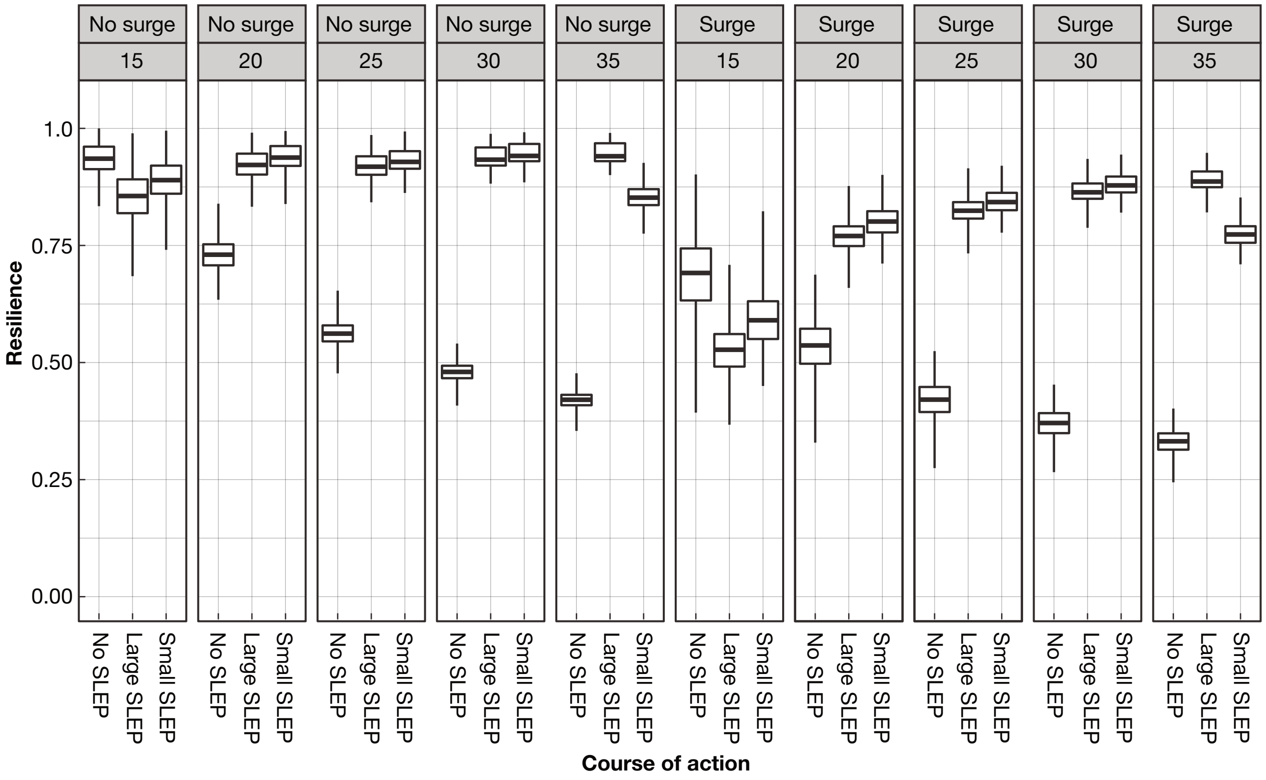


Figure 7. Program manager satisfaction resilience results for 15-, 20-, 25-, 30-, and 35-year time horizons with and without a surge in student matriculation.

Table 8 shows the program manager's preferred course of action for each functional outputs' resilience at each time horizon.

Squadron Commanders

The squadron commander applies the preference profiles and functional outputs defined in Table 7. As mentioned previously, every squadron commander has a 3-year time horizon. The squadron commanders are identified alphabetically.

When all aircraft life has been expended for a particular time period, that period has no commanding officers. Letters represent each commanding officer. The first commanding officer is Commander Alpha (A). The no SLEP course of action typically ends with Commander Foxtrot (F); the large SLEP course of action ends with Commander November (N); and the small SLEP course of action usually ends with Commander Kilo (K) but occasionally reaches Commander Lima (L). When a simulation runs out of aircraft, the commander receives no resilience value.

Table 8. Program manager preferred course of action

Surge Status	Time Horizon	Availability	Student Satisfaction	Graduates	
				Ephemeral	Permanent
No surge	15	No SLEP	No SLEP	Small	All
	20	Small	Small	Small	Large and small
	25	Small	Small	Small	Large and small
	30	Small	Small	Small	Large and small
	35	Large	Large	Large	Large
Surge	15	No SLEP	No SLEP	Small	Large and small
	20	Small	Small	Small	Large and small
	25	Small	Small	Small	Large and small
	30	Small	Small	Large	Large and small
	35	Large	Large	Large	Large

DISCUSSION

The study applied a hybrid resilience framework to a flight training squadron. The results show resilience to depend on time horizon for the program manager. With no delay in fielding a replacement system, the no SLEP course of action has the highest resilience in ready aircraft and student satisfaction. From 20 to 30 years, the no SLEP option becomes untenable and the small SLEP course of action has a slight advantage over the large SLEP course of action. The large SLEP option is the only tenable course of action at 35 years. The program manager would also look at resilience from the commanding officers' perspective. The program manager should avoid courses of action that make it impossible for commanding officers to meet their quotas. Figure 8 shows the sacrifice the commanding officers would make. The no SLEP course of action almost guarantees meeting the student satisfaction goals, with small SLEP and large SLEP becoming worse. Figure 9 shows resilience from the squadron commander's perspective. The type of SLEP changes the lifetime of the system and the resilience drop during the SLEP process (squadron commanders Delta and Echo). Resilience from the program manager's perspective does not capture these drops in resilience during the SLEP period. The program manager may prefer a large SLEP to maximize the lifetime of the fleet, while squadron commander Echo would see significant shortfalls.

The resilience results give more information to decision-makers than traditional measures of system availability, aircraft available to fly, or graduates per quarter. The resilience model provides stakeholder context to the system outputs. The framework is flexible enough to inform the "global" view of a program manager overseeing the entire life cycle of the system and to

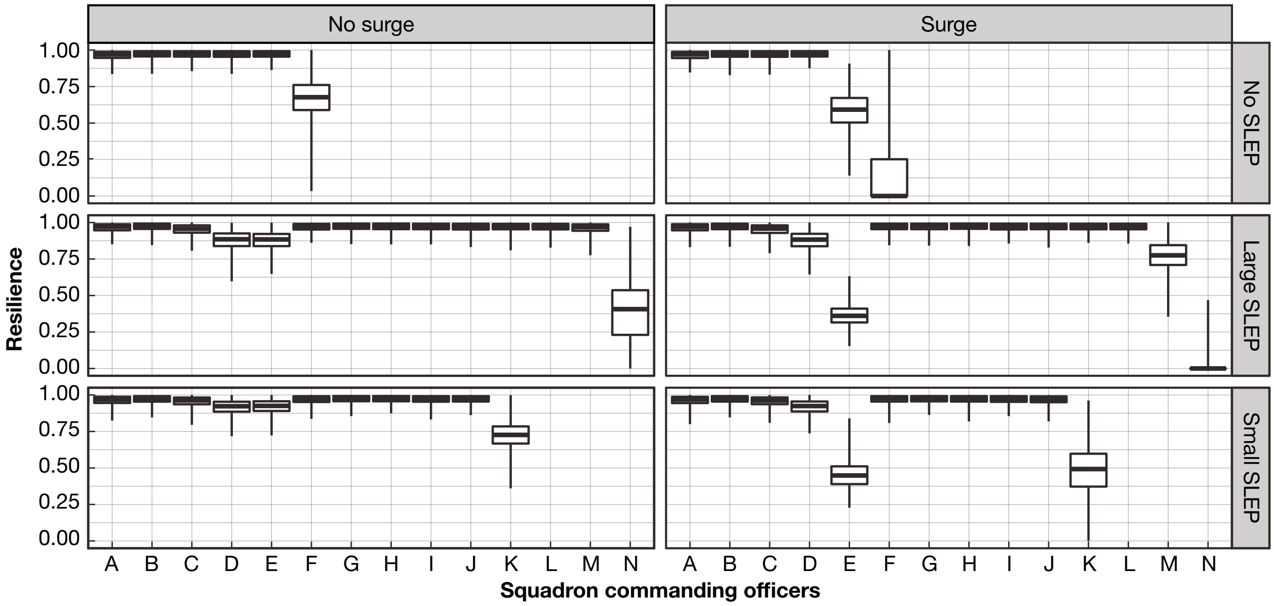


Figure 8. Squadron commander student satisfaction resilience results.

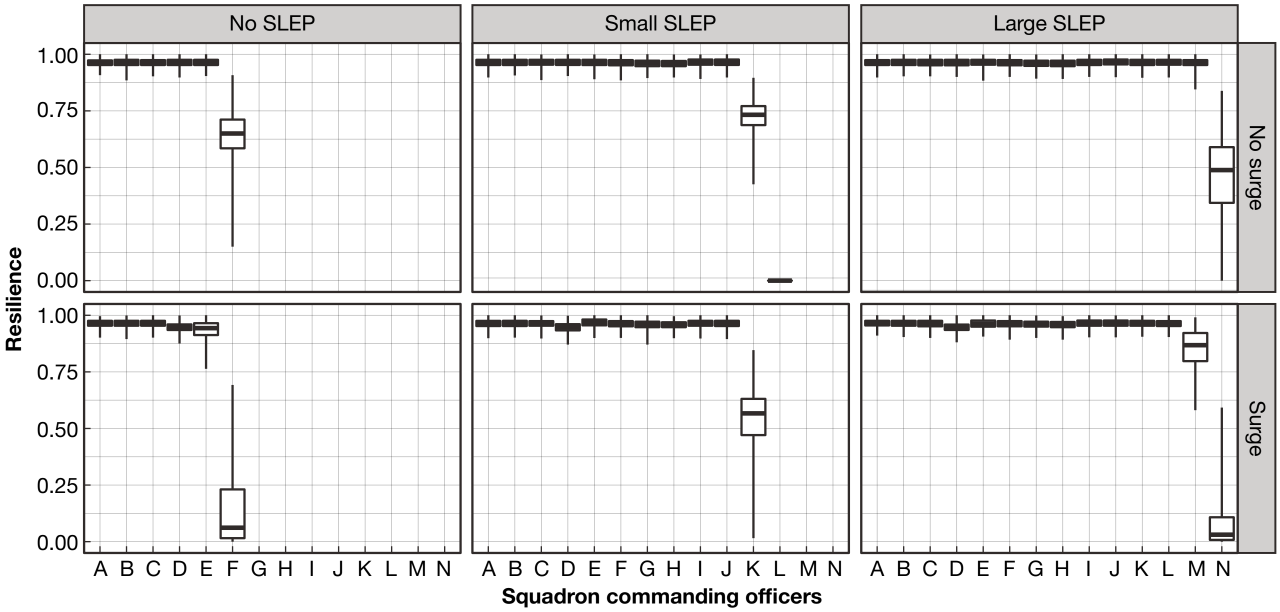


Figure 9. Squadron commander graduates per quarter resilience results ($\chi = 0$).

warn of “micro” issues occurring over the relatively small time intervals of a tour of command.

FUTURE WORK

The hybrid resilience framework aids a decision-maker considering multiple stakeholders and outputs of interest. One key goal for future work would be to explore the parameters that were held constant in this study to demonstrate how the framework performs when incorporating additional parameters. These include failure rates, attrition rates, and number of flights in the curriculum. Future work could look at varying more of the model parameters, introducing variable and multiple student surge production, and statistics for loss of aircraft.

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