A SYSTEMS ENGINEERING APPROACH TO STAFF SCHEDULING PROBLEMS, AS APPLIED TO FLIGHT CONTROLLER SCHEDULING AT NASA'S MISSION CONTROL CENTER

by

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Dedication

This study is dedicated to the men and women of mission operations, who have shown perseverance through many challenges. In control centers across the world, these engineers, technicians, and scientists silently put forward their best effort while sacrificing nights, weekends, holidays, and time with their families. You show the rest of humanity that dreams can become reality. Res gesta per excellentiam.

Acknowledgements

This project was only possible due to the tremendous people who surround me at home, in the work place, and at the University of Houston - Clear Lake. Many people have given me their time, support, encouragement, and patience since the glimmer of an idea for my thesis topic occurred to me a year ago.

First, I would like to thank my advisor Dr. James B. Dabney, whose wealth of practical experience has been essential in my quest to keep my university studies relevant to my full-time job at the Johnson Space Center. Without his guidance I never would have been able to meet my personal goals for this program.

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This research would truly have been impossible without the enthusiastic support and cooperation of my peers and supervisors in the Flight Operations Directorate. Many open-minded colleagues allowed me to dig deep into the how’s and why’s of their group scheduling practice, with little defensiveness. More impressive still, over the past 6 months the men and women of the ADCO flight control group have allowed me to overturn the applecart on their scheduling process and try out something new and innovative. Not all of my changes were good ideas, but the ADCOs are steely-eyed missile men and women; as a whole they embraced their new role as my guinea pigs.

Their gracious professionalism throughout this project has cemented what I already knew: that NASA's mission operations is one of the best places in the world to work.

My direct supervisors, Robbie Gest of KBR Wyle, George Chi of NASA, and Jeff Mauldin of NASA, deserve to be recognized for enabling this project and being stewards of innovation rather than red tape and bureaucracy. Thank you for your support and confidence.

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ABSTRACT

A SYSTEMS ENGINEERING APPROACH TO STAFF SCHEDULING PROBLEMS, AS APPLIED TO FLIGHT CONTROLLER SCHEDULING AT NASA'S MISSION CONTROL CENTER

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The flight controllers of NASA's Flight Operations Directorate (FOD) are the world's leading experts on human spaceflight operations. Despite this expertise, flight controllers for the International Space Station (ISS) Program, operating around the clock since 1998, struggle with the challenges of building effective staff schedules in a 24/7 operations environment. The existing literature in the operations research field includes optimization techniques that had not previously been applied to the flight controller scheduling problem. The application of these techniques are demonstrated in a case study utilizing the Attitude Determination and Control Officer (ADCO) flight controller group within FOD. The techniques are adapted to the flight controller staff scheduling problem within a systems engineering design process, thus bringing a full system level framework to bear on staff scheduling problems, a novel approach which incorporates the concepts of stakeholder analysis, requirements tracking, and design iteration to the field. The positive results demonstrate the effectiveness of systems engineering thinking when applied to new fields. A generic framework is outlined for use in any staff scheduling problem, along with recommendations for further development of these concepts.

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OVERVIEW

Introduction

Many industries require constant vigilance for the safe operation of their systems, services, and processes. Security, plant operations, air traffic control, hospitals, and other emergency services all require employees be on duty constantly. These 24/7 operations must be maintained without interruption by scheduling an unbroken chain of staff to fill their duties. The most effective schedules provide work-life balance and protect the health of the shift workers.

Solving such staff scheduling problems has provided an opportunity for research for the past half century. The mathematical problem itself - which has no limits on the size, as the schedule period can be increased indefinitely - has been a core focus of this research. A wide array of methods for optimization has been deployed against the problem: integer linear programming, greedy algorithms, branch-and-bound algorithms, and genetic algorithms, to name a few techniques. Given a set of clear constraints, one or more of these techniques can be utilized to generate a viable staff schedule, often rapidly.

However, the focus in the existing literature on the mathematical solution to the constraint problem has led researchers to ignore key considerations that are as important to the successful application of a staff schedule as finding an efficient and complete schedule solution. In particular, very little has been written regarding either the definition of constraints or the selection of the type of scheduling solution to employ. Often it is assumed that the decision maker has no questions in these areas.

Another area of interest, which is largely omitted from the literature, is discussion of different procedures for assigning real people to the theoretical schedules. An optimal schedule might be provided that shows how many operators are needed for a schedule, with fair days off, but the schedule still needs to be reconciled with the personal preferences and calendars of each individual operator. Several ranking schemes or other heuristic methods are available, which should be compared. If the shift assignment is perceived to be unfair (rarely are the available schedules exactly equitable) employee morale may be negatively impacted even if all other constraints and preferences are met.

While investigating current practices for staff scheduling within the Attitude Determination and Control Officer (ADCO) group within NASA's Flight Operations Directorate (FOD), it was found that all of these concerns were discussed during the scheduling process each quarter. Due to a dynamic workforce, staffing numbers change often, leading to re-assessment of the chosen schedule as well as the input constraints. A change in one step in the scheduling process often dictated a change in another. Therefore, a mathematically optimal schedule design is ineffective without good input constraints and clear rules for fair implementation.

A unique aspect of the flight controller scheduling problem pertains to workforce size. In most flight control groups within FOD, the number of operators in the worker pool is much greater than the number of operators needed for assignment each week. The standard assumption in the operations research literature is that only as many operators are on staff as are needed to provide a full schedule with fair days off. This does not apply to ISS flight control. Unlike plant operations for example, where an operator is either on duty monitoring a console or enjoying time off, for flight controllers the scheduled shift work is only one of the operator's duties. In fact, operators might spend a majority of their time in more traditional office work, which does not require a special staff schedule. This formulation of the staff scheduling has unique constraints which have not been explored previously in the literature.

Using the scheduling of NASA FOD flight controllers as a case study, a systems engineering approach was applied to staff scheduling problems. The results demonstrate the advantages of taking a systems level view of the staff scheduling problem. This approach includes the development of a cradle to grave procedure for each schedule period, with stakeholder analysis, constraint definition, schedule type selection, schedule design, and personnel assignment.

Through the development of this framework, tools were developed for various steps of the process. To assist with constraint definition, a structured stakeholder analysis is proposed. To assist with design of a repeating schedule, a formula for selecting a sub-period rotation based on dynamic staffing levels is provided. To assist with schedule creation, a simple linear programming solution is shown (solved here with OpenSolver, an open source Microsoft Excel plugin). To assist with fair personnel assignment to the schedule, various possible options are provided with selection criteria.

All of these tools were applied in two case studies on the ADCO flight controller discipline group within NASA FOD. First, the theoretical process is compared against 4 years of historical manually generated schedules. Second, the process is applied in practice over two real-life scheduling periods (Quarter 1 2019 and Quarter 2 2019). The results demonstrate that by applying systems engineering concepts to the problem of 24/7 operations staff scheduling problems a consistent, adaptable, and effective process can be implemented quickly and cheaply while meeting stakeholder requirements and preferences.

Background

A note on terminology: within this study the term "operator" is used generically to refer to any technician or engineer who staffs a console to monitor or operate a complex system, such as the flight controllers who staff the Mission Control Center (MCC) for the

International Space Station (ISS). Readers more familiar with flight controller training programs at NASA should not confuse the term “operator” with the alternate definition used by some groups which refers to junior flight controllers who have not yet earned the certification of “specialist.”

Overview of NASA operations and flight controller scheduling

The National Aeronautics and Space Administration (NASA) operates human crewed spacecraft missions from the MCC at the Johnson Space Center (JSC) in Houston, Texas. The men and women who staff the Flight Control Rooms (FCRs), looking after America’s astronauts day and night are the flight controllers of the Flight Operations Directorate (FOD). FOD has a long and storied history, being founded by the inventors of mission control itself, who first tackled the problem of remote mission operations as part of the Space Task Group, a small team operating out of Langley, Virginia in the late 1950s. The young flight controllers of today’s generation, who operate the ISS or are preparing to fly future deep space missions with Orion, trace an unbroken chain of mentors back to those original trailblazers who successfully launched America into the space age. Christopher C. Kraft, Jr., known to history as NASA’s first Flight Director, was an original member of the Space Task Group. His name now adorns the side of the MCC.

The knowledge of history and sense of duty to maintain traditions is a major asset to FOD. Flight controllers internalize lessons of excellence from the great flight directors of the past such as Kraft, Kranz, and other notable names from the first days of FOD (see Appendix A). The Foundations of Mission Operations, a code of ethics for safe and efficient human space flight operations, is posted on prominent placards throughout conference rooms at JSC (see Appendix A). While this sense of discipline and duty makes FOD a world leader in safe spacecraft operations techniques, it also makes them a conservative organization. Deviation from proven best practices presents risks; flight controllers are generally unwilling to take risks without data. Another outcome of the culture of perfection is that FOD tends to turn a skeptical eye on most techniques or tools developed outside of the organization. These two characteristics make change sometimes a slow process within the halls of mission control. Console shift scheduling is an example of a process that has suffered from a lack of innovation and implementation of outside ideas as a result.

NASA’s only active human spaceflight program (as of this writing in May 2019), the International Space Station (ISS) has been continually crewed by astronauts from 16 different nations since November 2001. This has required constant vigilance from FOD over the past 17 years. A team of anywhere from 6 to 20 flight controllers - plus their support staff - is always on console in Flight Control Room 1 (FCR-1), with no exceptions. Morning, noon, and night, every day of the year – weekends and holidays included – a team of expert flight controllers keep watch over the $150 billion dollar spacecraft orbiting at 220 miles altitude. Even through 2017’s Hurricane Harvey, as the JSC campus was drenched by flash floods from over 50 inches of rain, flight controllers camped out in the MCC, supporting their duty shifts. A sole exception to this rule was a ten day period following Hurricane Ike in 2008. During that storm and recovery, 24/7 operations continued but from remote sites away from the storm damaged city of Houston.

The ISS flight control team supports these 24/7 operations in a constant three shift daily rotation. Each shift is 9 hours in length, which allows up to an hour for the off-going team to handover to the oncoming team. The times of the shifts approximately follow the pattern of first shift being midnight to 9 am, second shift being 8 am to 5 pm, and third shift being 4 pm to midnight. For the remainder of this study, first, second, and third shift will be referred to as night, day, and afternoon shift.

The control moon mentioned above, FCR-1, can trace its history to the beginnings of the Apollo program in 1966. It supported its first flight as MOCR-2 with several unmanned Saturn rocket launches, followed by supporting the first orbital manned mission of Apollo, Apollo 7, in October 1968. ISS flight controllers working from FCR-1 today can look up at the walls of their control room and see the mission patches of the past missions operated from that room – starting with these early Apollo flights through the Space Shuttle program and finally the ISS program of today.

Figure 1 – MOCR-1 during Apollo 7

The ISS FCR is divided into many console positions dictated by areas of specialty (see Appendix B). The minimum staffing is a team of six consisting of a Flight Director, four disciplines responsible for operation of the ISS onboard systems, and a Ground Controller (GC) who monitors the health and status of the MCC itself and its network connections. These six disciplines must always be on console, three shifts a day. This presents a typical staff scheduling problem often seen in other industries, from hospitality to medicine to emergency response.

The problem takes the form of any 24/7 duty calendar that must be filled on a rotating basis by a pool of qualified operators. These operators can work a maximum number of days and also require a minimum number of days off from duty. The problem can reasonably be solved by employing a minimum team of four operators who are certified in each duty area (or ISS discipline). Three teams work the three duty shifts while a reserve team subs in at a regular interval to provide the required days off. After substitution cycles, a team will sub back in on a new shift in order to fairly distribute the different shifts. For instance, after working a week of day shift and taking days off, a team would sub back in on afternoon shift. This four-team approach is in fact how FOD achieved staff scheduling for the Space Shuttle Program. However, extending operations from a few weeks to the indefinite length of ISS operations presents additional challenges, and the four-team rotation becomes impractical if not impossible to implement.

Unlike nurses, EMTs, power plant operators, security guards, and other 24/7 duty shift jobs, FOD expects its flight controllers to perform a myriad of tasks in addition to their console duty in the MCC. In order to maintain their expert proficiency in their discipline, flight controllers are expected to support software testing, participate in simulation training, develop training materials, perform procedure validation, and attend various collaborative working groups, control boards, and operations panels. These duties could be suspended for individuals supporting a two-week space shuttle mission, to be resumed afterwards. For ISS operations, operators are expected to multi-task, supporting other duties one day and staffing the console the next. Multi-tasking ultimately means many more operators are required on staff in each discipline.

Figure 2 – The author and visiting Soyuz, 2014

An additional complicating factor is that not all FOD flight controllers are considered equal in skills and qualifications. Junior flight controllers tend to work more shifts (up to 40% of their billable hours) and are assigned to off-peak shifts such as nights and weekends. Senior flight controllers will work fewer console hours (sometimes as low as a day or two a quarter - enough to maintain proficiency) while the rest of their time is spent assisting flight directors and mission managers with decisions regarding the design, operation, and risk management of the flight program. Training astronauts or new flight controllers can require a significant time commitment from Instructor Flight Controllers (IFCs) who are usually considered the most senior in any group.

A common project assignment for senior flight controllers is to be assigned to a Joint Operations Panel (JOP) team for a specific on-orbit operation such as a cargo vehicle flight or software upgrade. These flight leads, as they are often called, are expected to follow all the details of the JOP topic for their discipline. Participating in their assigned JOP is a higher priority than routine console operations, as they are the only person in the loop on the JOP, while any other team member can fill in on console.

Due to these factors, any console scheduling process used for FOD flight controllers must be flexible and adaptable. The process must allow for a large group of operators in a scheduling period. The process must also allow for a large ratio between the operator assigned the most shifts per schedule period and the operator assigned the fewest.

FOD disciplines assign flight controllers to console on a group-by-group basis, without any constraints between groups. For example, the scheduling choices made by the electrical power specialist group do not affect how the environment control and life support group assigns their operators to console. Scheduling processes are independently designed and implemented within in each group. While there is some variation across groups, the general methods for scheduling follow a similar style across all ISS operations disciplines.

The scheduler (usually a group lead or their designee) will first gather inputs: number of available operators and their demographics, calendar for the scheduling period, operator preferences, and operator personal leave schedules. Using these inputs and a set of constraints or guidelines, the scheduler will manually construct a spreadsheet representation of the schedule, ensuring that each calendar day has three shifts of operators assigned, plus a fourth person on-call in case of contingency or illness. The scheduler generally has the following goals in mind:

- Schedule completion (no gaps in assignment)
- Respect of personal leave and preferences
- Fairness or balance between operators
- Honoring constraints and guidelines
- Night shift assignments are fair/healthy

In order to achieve these goals, the manual process often requires iteration as well as communication with management (who defines the constraints) and the operators themselves (who define their leave and personal preferences). It is common for at least one of these goals to be unmet. For example, in one of the ISS system specialist groups in 2018, there were several scheduling periods in which some shifts remained unassigned at the time the schedule was published; volunteers had to be found closer to the date of the unassigned shifts. Estimates of the number of hours required for this process, which is widely done on a quarterly basis, was reported by schedulers to take anywhere from 10 to 40 hours, depending on the specific details of how the process is iterated.

Commonly cited frustrations with the current scheduling processes in FOD for ISS operations include: scheduling process or schedule is not fair, too many shifts assigned to some operators, too many or too few days worked in a row, too many or too few people working per week, and allocation of night shifts is unhealthy.

Issues related to personal preferences or a sense of fairness are subjective and require a stakeholder analysis to better understand and accommodate. While internal informal stakeholder analyses are commonly conducted within each FOD discipline, no record of any previous large-scale stakeholder analysis could be found.

Issues related to efficiency require a quantitative approach to the scheduling process. Presently, the staff scheduling processes used by all six of the 24/7 support disciplines use entirely manual processes. No optimization solutions are currently utilized for shift assignment. Likewise, no quantitative approaches are used to define constraints or ideal sub-period rotations.

Issues related to the health impacts of shift work (especially working night and afternoon shifts) require a review of occupational health research. FOD has previously allowed research into flight controller health impacts of shift work, including an in depth study with Harvard. However, the findings and recommendations of this study - or the general standards of care recommended by the occupational health industry - have not been implemented as input constraints to the current console shift scheduling processes.

The flight controller scheduling problem presents significant opportunity for implementation of existing optimization techniques and industry best practices. Based on a thorough stakeholder analysis and literature review, specific opportunities for change can be identified. With data in hand to demonstrate possible improvement in efficiency of work and employee satisfaction, it should be possible to design new staff scheduling processes that will be accepted by flight control discipline managers.

Systems Engineering Process

Systems engineering is defined by the International Council on Systems Engineering (INCOSE) [**1**] as

"...an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: Operations, Performance, Test, Manufacturing, Cost & Schedule, Training & Support, Disposal."

When systems engineering is implemented, the designer will consider all aspects of the system's use and application during all design phases. A design effort that utilizes a systems engineering process will be characterized by traceability, feedback between design phases, and performance validation against requirements.

An engineered system is designed for the entire system life cycle. A common top level breakdown of the system life cycle phases includes four phases: design, construction, utilization, and end-of-life. A systems engineering process includes key milestones or activities during each of the life-cycle phases. Below is a summary of the life-cycle milestones that should occur in each phase.

Design phase

- Needs identification

- Stakeholder analysis
- Performance measure or requirement definition
- Prototype development
- Design iteration

Construction phase

- Prototype testing
- Design iteration

Utilization phase

- Maintenance activities
- Stakeholder or customer feedback
- Performance assessment/lessons learned

End-of-life phase

- Safe disposal or archival
- Closure reviews
- Lessons learned documentation

In summary, systems engineering is a method of designing a system or process using quantifiable metrics and feedback between design stages or iterations in order to maintain and improve the system. The simplest representation of this process is the waterfall process model, as shown in Figure 3.

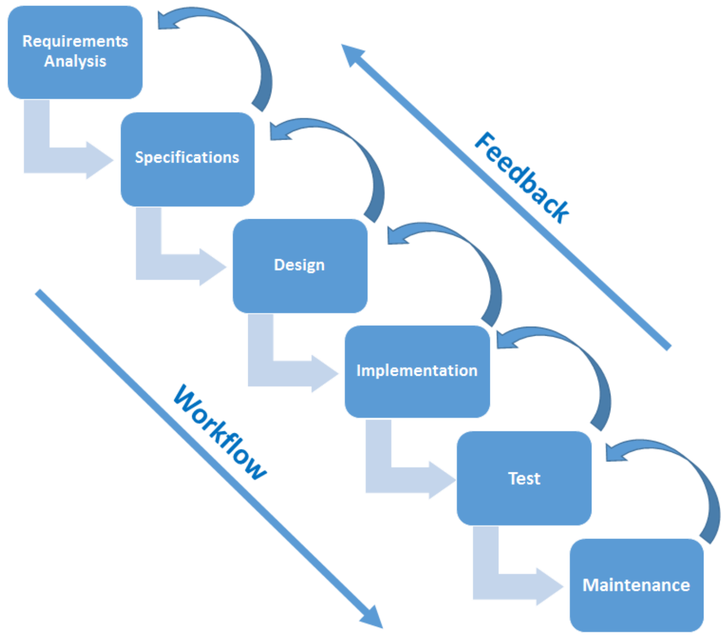


Figure 3 – Waterfall Process Model

The stakeholder analysis and literature review below reveal that the staff scheduling process has not previously been approached as a system or process that can be engineered. Through the following case study, the staff scheduling process for flight controllers at NASA's Flight Operations Directorate (FOD) is redesigned using systems engineering concepts. Stakeholder interests are used to define requirements. Performance is tracked against these requirements over subsequent schedule design iterations. This performance trending is used to define an optimal process to improve efficiency, safety, employee health and satisfaction, while reducing cost for the customer.

CHAPTER II:

PRELIMINARY RESEARCH

Stakeholder Analysis

The DOD's Defense Acquisition Guidebook (DAG) Chapter 3, Systems Engineering [**2**], lists 8 technical processes to effectively bring a system into being. The first two are Stakeholder Requirements Definition and Requirements Analysis. Taken together, these two steps can be referred to as a Stakeholder Analysis. Clearly defining stakeholder interests and defining measurable requirements are hallmarks of an engineered system. An appropriate solution can only be found for a well-scoped problem. A robust stakeholder analysis ensures that the right problem is addressed.

A thorough stakeholder analysis was conducted on the six ISS flight control groups who operate on a continuous rotating shift schedule. Current scheduling practices were recorded, operators were surveyed, and stakeholder interests were identified and ranked. The results of the stakeholder analysis were then used to organize the findings of the literature review to identify applicable solutions.

Identification of Stakeholders

This project seeks to optimize the design process for the quarterly shift schedule of flight controllers in NASA's MCC. Therefore, the stakeholders are those people or groups affected by the rotation of personnel through assigned console shifts. This should include the flight controllers themselves, but also decision makers and customers.

When identifying stakeholders, it is often useful to identify which stakeholders are external or internal to the organization. Console scheduling policy and processes are determined at the discipline group level within FOD. Therefore, stakeholders within each discipline will be considered internal and those not reporting to discipline level management will be considered external. A simplified FOD organizational chart is provided for reference, showing the level at which staff scheduling decisions are made for the ADCO flight controllers within the ISS Guidance, Navigation, and Control (GNC) branch.

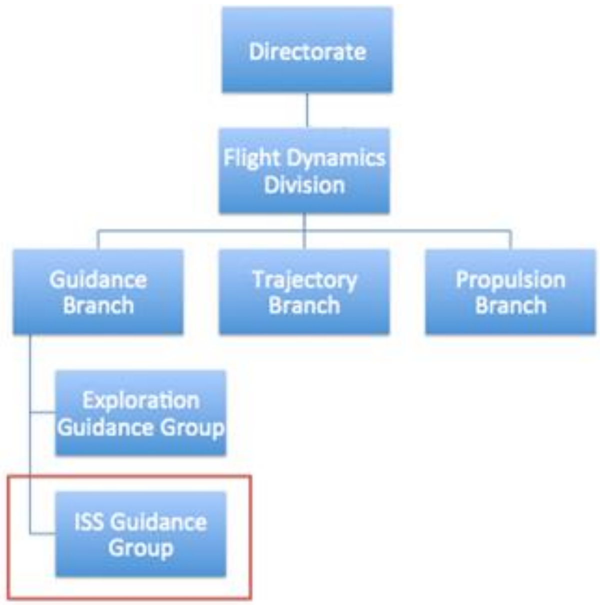


Figure 4 – FOD Organizational Chart

Therefore, any stakeholders within the ISS GNC group were defined as internal and all others external. Based on this definition, the internal stakeholders are the flight controllers, group managers, and group schedulers (when there is a separate scheduler from the manager). The group managers and group schedulers are referred to together as the group decision makers.

To understand the additional external stakeholders, further background on the structure of NASA flight operations and management of the ISS program is required.

The Flight Operations Directorate (FOD) provides flight operations support for all human spaceflight programs. At the time of this writing, this includes International Space Station (ISS), Orion Exploration, Commercial Crew Program (CCP), and Lunar Orbital Platform-Gateway (Gateway). Each program has its own management structure separate from the FOD management structure shown above. Therefore, a FOD flight controller supporting two programs (for instance, ISS and CCP) would have three management chains interested in their performance.

Within the flight control room itself, during real-time mission support, there is an additional chain of command. Each flight control discipline may have both front room personnel (FCR) and backroom personnel (MPSR). The MPSR personnel report directly to their respective FCR. Each FCR then must report to the Flight Director, who is responsible for the overall safe and effective operations of the spacecraft while on duty. The flight director is the ultimate decision maker for the mission for all real-time decisions made in the MCC.

Each of these chains of management has an interest in the success of the mission. Therefore, they also have an interest in the choices made in the design of the flight controller schedule.

The complete list of identified external stakeholders includes:

- Other FOD management (Branch, Division, Directorate)
- Flight Directors
- Customers (astronauts, ISS program management, taxpayers)

Internal Stakeholders

Interviews and surveys were conducted to determine the needs and preferences of the internal stakeholders. First, interviews with the group decision makers provided insight into the current scheduling process and constraints.

Interviews were conducted with either schedulers or managers (or both) from each of the 6 groups. It was found that scheduling processes can be described on a spectrum from self-assignment to manager-assignment. In self-assignment, operators are provided with constraints and/or quotas for their shifts and then select which days they will work in the schedule. In manager-assignment, the decision maker chooses the shifts for the operators. Some of the groups utilized hybrid methods in which operator preferences (for example “I prefer night shifts to afternoon shifts”) are taken into consideration. Table 1 shows the scheduling methods used by each of the 6 groups. In all cases, these scheduling methods involved manual shift assignment, no optimization.

A common method for organizing the operators within each group for scheduling is to use categories based on their seniority, certification, or task loading. These categories are referred to as “buckets.” Each group that used buckets had their operators grouped into 3 or 4 buckets, with each bucket having their own constraints. A bucket constraint is any constraint that is dependent on the bucket type for implementation. An example bucket constraint might be that bucket 2 operators cannot work the day shift, or only a certain number of bucket 4 operators should work during the same week. By contrast, an example of a non-bucket constraint would be to ensure that no operator is assigned to work two weekends in a row.

Table 1:
Scheduling methods in mission control

	Group A	**Group B**	**Group C**	**Group D**	**Group E**	**Group F**
Schedule Method	Self-assign	Manager-assigned	Hybrid	Self-assign	Manager-assigned (teams)	Hybrid
# Operators	~30	~24	~36	~24	~15	~24
Bucket constraints	Yes	No	Yes	Yes	No	Yes
Hrs./quarter	12	3	8	6	16	40

The sections below provide a more detailed description of the ADCO scheduling process, followed by an overview of findings from decision maker interviews, flight controller surveys, and external stakeholder review. The stakeholder analysis concludes with a table summarizing the stakeholder interests mapped to the scheduling process and a prioritized ranking of those interests.

For detailed descriptions of the differences between the scheduling processes for the other 5 groups that were surveyed, see Appendix B.

ADCO Scheduling Process

ADCO employs a 13-week, or quarterly, schedule period. As with all FCR flight control positions in FOD, a single operator must be on console for each 8 hour shift, three times a day, 7 days a week. Therefore, there are 273 (13*7*3) individual shifts to fill in the schedule period. Additionally, as with all FCR flight control positions in FOD, ADCO employs an on-call system in which a fourth operator is on-call for a 24-hour period. The on-call is available in case of illness or other contingency. Therefore, the total individual assignments made for each schedule period is 364 (273+13*7).

ADCO employs a 7-day sub-period within the schedule period. Flight controllers are assigned in a pattern that repeats every sub-period. This pattern is referred to as the "weekly schedule rotation." The legacy weekly schedule rotation for ADCO uses seven operators per week. In other words, the week is divided into seven shift blocks, as shown in Figure 5 below (note that the shift notation represents Night, Day, Afternoon).

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
N	J1	J1	J1	J1	J2	J2	J2
D	J3	J3	J4	J4	J4	J5	J5
A	J6	J6	J6	J6	J7	J7	J7

Figure 5 – Legacy ADCO 7-block rotation

Using this strategy of shift blocks has two effects on the schedule process. First, it reduces the number of shift assignments in the schedule period from 273 to 91 (13*7). Second, it makes the schedule predictable, as the pattern repeats every week (although often with different operators). Each operator is assigned a quota of blocks they must support in each schedule period. The quotas are meant to balance the workload across the workforce. Generally, junior flight controllers are assigned a larger quota (such as, four blocks of either J1 or J2 shifts, one block of J7 shifts, and two blocks of J5 shifts, for a total of ~21 days). Senior flight controllers may be given a very low allocation (such as, two block of J3 or J4 shifts and one block of J6 shifts for a total of ~9 days).

Once the quota is determined, the group scheduler generates a spreadsheet representation of the schedule with a column for each day and a row for each operator. The spreadsheet is posted to a shared drive and the operators are notified that they can sign up for the blocks of their choice. Shift assignment then proceeds in a first-come first-serve manner; operators self-assign blocks by filling in the spreadsheet.

On-call scheduling is handled in a similar manner to console shift scheduling. Each of the 13 weeks in the schedule period is broken into a block of 5 week days and 2 weekend days. These 26 blocks of on-call assignments are then allocated (based on management directive) to the senior flight controllers who self-assign using the shared spreadsheet.

In the event of a change in the operator pool, such as an employee's retirement, the remaining operator pool must now fill the shifts that were previously selected for the departing operator. This is generally done on a volunteer basis.

Decision Maker Analysis

Based on the interviews with group decision makers from all six groups, the following metrics were identified as the most important factors considered when designing an operator console schedule in FOD.

- Consideration of operator preferences or choices
- Delivering schedule on time

- Completeness of schedule (no unassigned shifts)
- Availability of senior operators for other tasks
- Fairness/health impacts of schedule

Two hard constraints apply to all flight control schedules. First, a flight controller must always be on console for each shift. This is in contrast to staff scheduling problems in other industries – such as service industries – where some over or under scheduling compared to demand is accepted. Second, flight controllers must be proficient in their flight control discipline. Proficiency is defined as having staffed at least one console shift prior to a management defined deadline.

In addition to these hard constraints, the schedulers operate under external guidelines imposed by FOD management via the "ISS Real-Time Support Work Guidelines" memorandum, distributed by the Director of Flight Operations. These guidelines can be summarized as:

1. Operators should only support either console work or office work on a given day, never both.
2. Night shift work should be scheduled with sufficient time to sleep shift (see, adjust).
3. Operators can only work a maximum of 10 consecutive console shifts.
4. Operators should receive sufficient time off between shifts and returning to any kind of work, including at least half of weekends off per month.
5. Total hours worked over a timecard period should be kept within a defined limit.

Within these constraints and guidelines, group decision makers have freedom to design any type of staff schedule they deem convenient or appropriate. Unconstrained parameters include but are not limited to: minimum number of days assigned, minimum number of days off between shifts, and minimum or maximum number of night shifts.

Additionally, operators are allowed to self-manage their schedule and choose whether or not to report for office work the day before or the day after their console shifts.

In addition to the external guidelines, each of the groups has independently identified additional guidelines that they try to meet during the design of each schedule period. These internal guidelines and the weekly schedule rotation are considered changeable, but are not necessarily adjusted regularly. For instance, the most recent ADCO schedule period prior to this case study (Quarter 4 2018) used the 7-block rotation in Figure 5. However, prior to that quarter a 5-block rotation had been used for at least the previous 5 years. This previous rotation is shown in Figure 6.

	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu
N					J1	J1	J1	J1	J1	J1	J1
D	J2	J2	J2	J2	J2	J3	J3				
A	J4	J4	J4	J4	J5	J5	J5				

Figure 6 – Legacy ADCO 5-block rotation

Guidelines used as inputs to the schedule design take various forms. Some groups apply strict shift block limits or quotas. Some groups apply non-block quotas for minimum or maximum days worked in a quarter. Some groups apply non-block constraints for minimum days between shifts. What is common to all groups is that these guidelines are based on the experience and intuition of the group decision makers. There are no traceable requirements used to define the constraints.

The block constraints are intended to balance out the workload in a way that is proportional to the operator’s task assignments. Key aspects of the FOD work environment give managers both the desire and ability to have a wide disparity in the number of shifts supported each schedule period within their group: operators support many tasks and programs in addition to console duty, groups have many more operators than traditionally necessary to complete a three-shift rotation schedule, operators are only required to meet a minimum proficiency number of shifts (see External Stakeholders).

This leads to the proportional assignment practice referred to above. Generally, the most junior flight controllers will work many more shifts than those of higher seniority. Additionally, the junior flight controllers will work more weekend, afternoon, and night shifts. The objective of the group managers by implementing this strategy is to ensure that qualified personnel are available to support the myriad of off-console responsibilities of each group. This metric, referred to for the rest of this study as “senior flight controller availability” is not currently tracked with a traceable requirement in the flight controller console scheduling process.

All guidelines can be deliberately broken during the scheduling process if the scheduler deems it necessary. In bottom-up scheduling (as is currently done by FOD groups) constraints are most often broken when the schedule faces a dilemma which leads to a cascade problem. A scheduling dilemma is a problem faced in bottom-up scheduling when there remain unassigned shifts, but no operators can be assigned to those shifts without violating a constraint. A detailed example of a scheduling dilemma and the following cascade problem is described in Appendix D. Dilemmas are often encountered every cycle by groups that do self-assignment. Dilemmas are less often encountered by groups that do manager-assignment, but they do still occur if the scheduling problem has been over-constrained. When faced with a dilemma and cascade problem, the scheduler has two options: start the schedule over or violate a constraint to complete the schedule. In the interest of delivering a complete schedule on-time, most FOD decision makers consider it acceptable to violate guidelines in order to solve the schedule faster, rather than start over.

In some dilemma cases, FOD decision makers have decided to deliver an incomplete schedule. In these cases, the shifts that have been successfully assigned are made official on calendars while the remaining unassigned shifts must be filled in by volunteers or manager-directed assignment. The most common method is to allow the shift blocks to be broken up into individual shifts and operators will volunteer for individual shifts they can support.

The top interests of the group decision makers are summarized and prioritized in Table 2 below.

Flight Controller Surveys

Survey data are shown below for 47 responders from three of the 24/7 operations disciplines (ETHOS, ADCO, and CRONUS). Surveys were conducted using multiple choice and free text web surveys created on SurveyMonkey.com. The surveys were conducted on each group separately and the questions asked were not identical. In some cases questions were asked of only some groups. The complete unedited survey data is provided in Appendix C. The surveys were designed to understand flight controller preferences on several topics. Operators were asked questions related to the design of the weekly rotation, distribution of night shifts, and preferences for working weekend shifts. They were also asked a question intended to gauge openness to trying new methods of scheduling. The detailed results of these survey questions is discussed below.

The operators were asked about their preference for number of days worked in a shift block. The options provided for response were “2 to 5”, “6 to 7”, or a comment field. Two responders opted for the comment field; both of them responded that the answer depends on the time of day of the shift. One of them stated that they want to work longer shift blocks for night shifts but shorter shift blocks for day shifts and afternoon shifts. The other responder stated that they want to work 2-5 days for day or afternoon shifts but as few as possible for night shifts. The third "special" response was a single responder who chose a survey response option of "select each day individually" (i.e., do not schedule in blocks). The shift block preference data demonstrate that for most flight controllers, morale will be impacted if they are scheduled for long shift blocks.

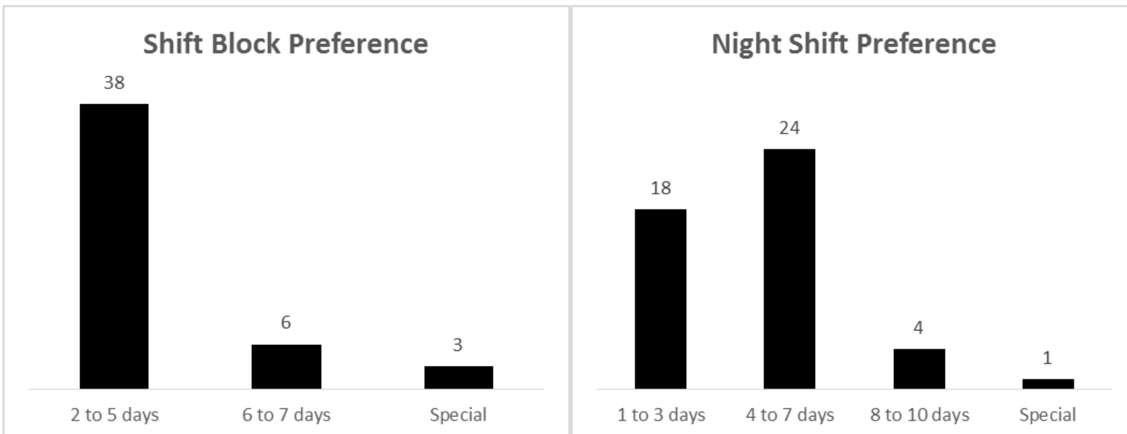


Figure 7 – Shift block length preferences

Flight controllers provided their preference for the length of a night shift block (a more specific framing of the shift block length question). Responders were given three choices for the number of days worked in a block of night shifts: "1 to 3", "4 to 7", or"8 to 10". They could also respond in a comment field. The 8 to 10 option was provided here but not for the generic block length question due to the conventional wisdom often cited in FOD that once one is already working night shifts, it is better to work as many as possible while adjusted. The single responder who opted for the comment field stated that they would like the night shifts split between the weekdays and weekends due to family impacts.

There is no consensus among flight controllers about the right number of days in a row for night shifts. 38% of responders want shorter shift blocks while 60% want longer shift blocks (combining the second and third responses). Therefore, having a mechanism for flexibility in scheduling night shifts may be important to morale. However, it was found in the literature review that many operators' preferences for length of night shift blocks disagree with the state of the art in sleep science. Ultimately, it may be more important to follow those recommendations than try to meet operator preferences.

Closely tied to preferences for length of night shift blocks is the issue of "sleep shifting." Sleep shifting is the act of adapting a sleep schedule before and after a shift block in order to match the operator's circadian rhythm to the planned work schedule. Flight controllers were asked how many days it takes them to sleep shift before and after a block of night shifts.

The responses show a wide variation in flight controllers' relationship with sleep. Two responders (4%) selected an answer of zero days while fourteen (30%) said three or more. In the middle of the distribution, eleven responders said one day (23%) and twenty responders said two days (43%).

(Note: half of responders could answer 3 or more than 3 as answer. The other half only had an option for "many days." A selection of "many days" was counted as 3+)

It was suspected that there would be a correlation between the reported number of days required to sleep shift and the preference for the length of night shift blocks. Therefore, the two categories are compared in the second chart in Figure 8. The data shows a cluster around a shift block length of 4 to 7 days, regardless of sleep shift days. It cannot be concluded from this data which other factors besides sleep shifting are affecting these preferences. Further survey data is needed, possibly with more granular choices for shift block length.

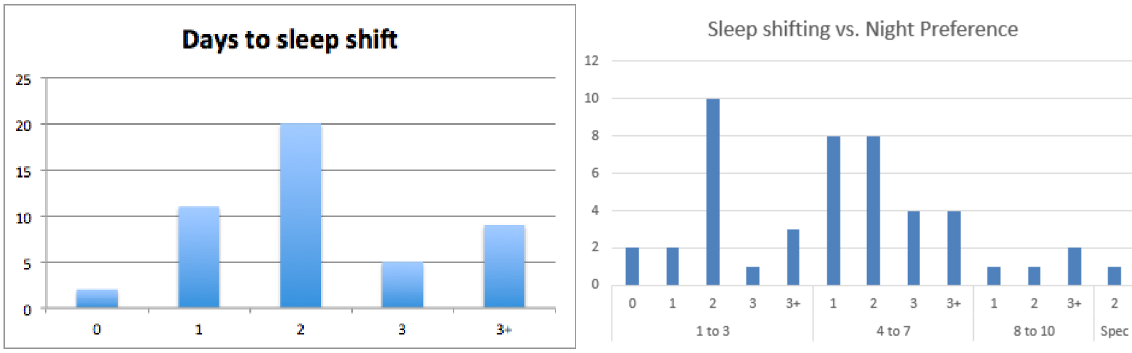


Figure 8 – Sleep shifting survey data

Regardless of their specific preferences, all flight controllers have strong opinion about night shifts. Most flight controllers feel a strong impact to their work and personal life from supporting night shifts. Work-life balance for shift workers is challenging. As such, very few flight controllers would assign themselves night shifts if given the option. Figure 9 shows that 74% of responders ranked night shifts as their last preference.

(Note: this question only went to 23 of the 47 operators surveyed)

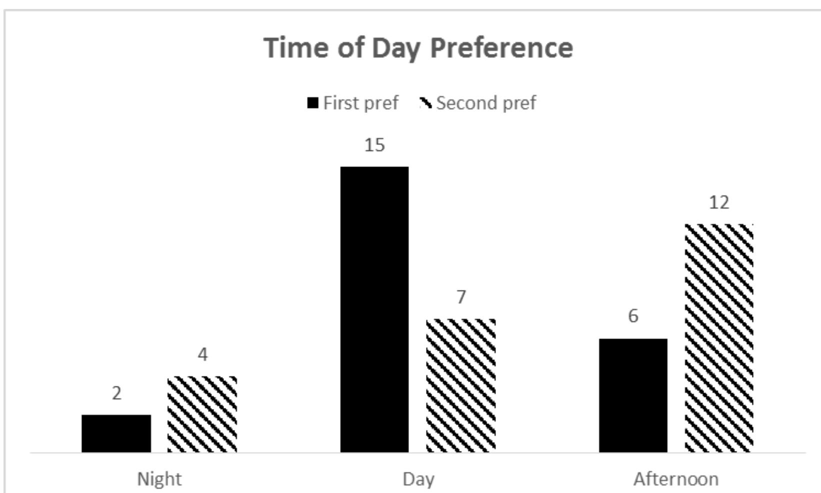


Figure 9 – Shift preference survey data

The surveys included two questions related to weekend shifts. First, operators were asked whether they prefer to work the entire weekend or always have at least one weekend day off when working the weekend (split weekend). Second, they were asked whether they prefer to work the weekend only or if weekend and weekday shifts can be combined into the same shift block. The responses are shown in Figure 10 below.

Figure 10 – Weekend preference survey data

The data show that responders are divided on the question of how to assign weekend shifts. Nearly half of responders (43%) prefer to have part of their weekend free when working at least one weekend shift. Another 43% of responders would prefer to work through the entire weekend when working a weekend; presumably to bank the vacation time for later use. Responders were similarly divided on the second question. A large minority of responders (35%) do not want weekend shift blocks combined with any weekday shifts, while another 53% of responders said that weekend and weekday shifts can be assigned together. The framing of this question does not make it clear if that majority thinks weekend and weekday shifts should be combined or if they merely are accepting of such a design.

Operators were also surveyed about the design of the overall schedules. The first question pertained to rotating schedules. An example of a rotating schedule is provided in Figure 11. In this schedule, an operator rotates through all three types of shifts in a 6-day shift block. The change from one shift type to the other is used to make sleep shifting more efficient. Rotating schedules are discussed more in the literature review.

	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed
Oper 1					D	D	A	A	N	N
Oper 2			D	D	A	A	N	N		
Oper 3	D	D	A	A	N	N				

Figure 11 – Example rotating schedule

There was a strong desire from responders not to utilize a rotating schedule. Only 30% of responders said they were willing to try rotating schedules or had no preference. 70% of responders said they would not be willing to try rotating schedules.

Operators were also asked about frequency that the schedule pattern repeats, or the length of the schedule sub-period. All FOD groups surveyed use a weekly rotation, or a 7-day sub-period. Operators were asked if they would prefer 7, 10, 14, or 30 days for the sub-period length. (Note: this question was only asked of 24 of the 47 responders)

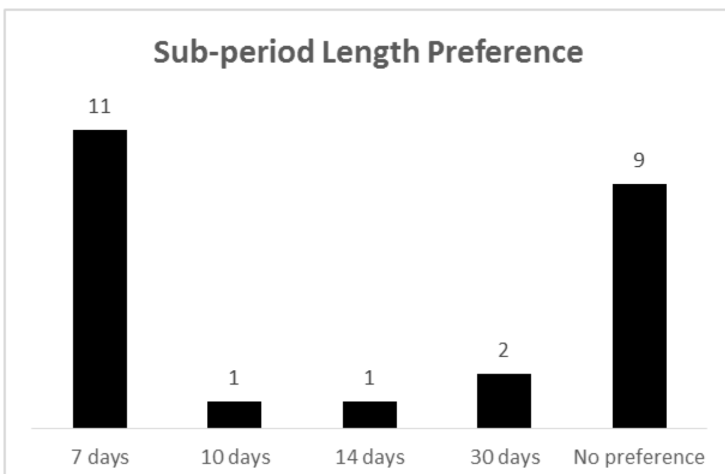


Figure 12 – sub-period length preference survey data

The responses show that 46% of responders prefer to continue with the current 7-day sub-period while the remaining 54% seem open to trying longer schedule patterns.

Given the variation in responses to all of the survey questions, there are no specific schedule design parameters that can be defined based on operator preferences. However, it is clear that providing flexibility in the number and types of shifts that can be assigned will increase operator satisfaction. Additionally, the unwillingness to try drastically new types of schedules is a possible indicator that operators are focused more on the effects of sleep shifting and days off scheduling than other concerns.

The top operator interests are summarized and prioritized in Table 2 below.

External Stakeholders

Three separate groups of external stakeholders were identified: Flight Directors, FOD management, and customers. These stakeholders were analyzed using interviews and requirements document review.

FOD Management

The FOD management interests are represented by the guidelines from the "ISS Real-Time Support Work Guidelines" memorandum. In addition to these written requirements, FOD management requires regular reporting of staffing levels from every flight control group. Group managers must report a "red, yellow, or green" staffing level compared to expectations. The staffing levels are meant to reflect the number of employees certified to support console shift operations.

Flight Directors

A representative of the flight director office was interviewed to investigate their interests as stakeholders in the flight controller scheduling process. Based on this interview, the flight director expectations can be summarized as meeting the external guidelines listed above while building intelligent schedules that minimize the risk to operations. Risk is minimized by allowing operators to have a reasonable work-life balance and not be overworked between their console and off-console tasks. These flight director interests are summarized in Table 2.

Customers

There are three different customers who benefit from the successful execution of operations in the MCC: ISS program management, astronauts, and the American taxpayer. All three of these customers realize these benefits when the mission is executed safely, efficiently, and within budget.

The external stakeholder interests are summarized and prioritized in Table 2.

Summary of Stakeholder Interests

Table 2 summarizes the findings of the stakeholder analysis.

Table 2:
Stakeholder Interests

	Stakeholder	Interests	Stakeholder Priority
Internal stakeholders	Decision Makers	Guidelines met Schedule completion Operator preferences Perceived fairness Health/fatigue impacts Senior operator availability On-time completion Hours spent on schedule	High Medium Low Low Medium High High Low
	Operators	Schedule completion Operator preferences Perceived fairness Health/fatigue impacts On-time completion	Medium High High High Low
External Stakeholders	FOD Management	Guidelines met Senior operator availability Cost	High High Medium
	Flight Directors	Guidelines met Health/fatigue impacts	High Medium
	Customers	Guidelines met Health/fatigue Cost	Medium High High

It is important to note that not all interests are mutually independent. In some cases they are closely interrelated. Two relationships worth highlighting were identified.

First, the operators are not as interested in schedule completion as a fair and healthy schedule. However, when a schedule is left incomplete, the operators who must volunteer for the remaining shifts often end up with the least fair or healthy schedules for that schedule period.

Second, many of the internal guidelines are designed to improve senior operator availability. When guidelines are bent to resolve dilemmas, it is usually in order to preserve other constraints that maintain senior operator availability. Therefore, decision makers must lower their priority on one of their interests (guidelines met) for another (senior operator availability).

It should also be noted that all stakeholders consider the safe and successful execution of the mission, as well as the health and wellness of all flight controllers, as a top priority. Table 2 is not meant to imply by omission that these objectives are less valued by some stakeholders. Rather, this list of interests reflects the metrics that each stakeholder most commonly uses to assess a flight controller schedule.

The stakeholder analysis shows that there are measures of both the effectiveness of a shift schedule and of the process to develop that schedule which should be tracked against a benchmark value. Based on the data above, the following performance measures should be used when developing a schedule for flight controller groups within NASA's FOD, and the ADCO group specifically. Benchmark values are given below in the Methods section.

Performance measures:

- Hours spent on schedule
- On-time delivery

- Operator satisfaction with
    - Fairness
    - Preferences
    - Health impacts
- Constraints met
- Senior operator availability
- Schedule completion

Literature Review

A literature review was conducted to determine if existing solutions were available which could meet the scheduling needs of NASA FOD's flight controller groups. Three types of publications were reviewed: staff scheduling, occupational health, and any applicable studies that have been done on NASA flight controllers directly (of which there have been a handful).

The review revealed a synergistic opportunity between the field of staff scheduling research and the flight controller scheduling problem at the MCC in Houston. While there are many techniques and tools that have been developed for staff scheduling problems, there are also unique features of the flight controller scheduling problem that have not been specifically explored in the existing literature.

Staff Scheduling

The literature on the staff scheduling problem as a formal quantitative problem extends back decades. The problem is generally approached as a set-covering problem, first addressed by George Dantzig of the Rand Corporation [**3**], who addressed the scheduling of tollbooth operators. Since that time, an entire sub-field of mathematics has explored the problem and its related sub-problems. Ernst's 2004 review of the research [**4**] cites 194 different works. A doctoral thesis entitled "The staff scheduling problem: a general model and applications” by Marta Soares Ferreira da Silva Rocha [**5**], of the University of Porto in Portugal, cited another 92 works (including some overlap with Ernst).

The field of staff scheduling research is vast, covering many types of work environments and scheduling problems. Ernst [**6**] provides further insight into the field in another review work in which he outlines a generic six-step definition of the staff scheduling problem, which can be applied regardless of the work environment. This six-step definition is useful when exploring the research, as it can be used to define which portion of the problem is explored in a particular work. Ernst’s six steps are shown below, followed by a discussion of their definitions.

1. Demand modeling
2. Days off scheduling
3. Shift scheduling
4. Line of work construction
5. Task assignment
6. Staff assignment

Demand modeling refers to a definition of the required number of employees or operators during each unit of time in the schedule. Days off scheduling refers to determining the number and frequency of days off in the schedule period. Shift scheduling refers to selecting the start and stop times of each shift in the daily rotation. Line of work construction refers to building a set of schedules, of a number equal to the number of teams or employees to be assigned. Task assignment refers to determining which tasks are occurring on which shift, which may set constraints for who can staff those shifts. Lastly staff assignment refers to assigning specific operators or teams of operators to the lines of work.

Ernst himself points out that some of these steps may not be required in all staff scheduling problems. For instance, Ernst says "[The shift scheduling step] is, obviously, redundant when rostering to shift based demand," by which he means schedules which always use a three shift rotation, as in the flight controller scheduling problem. Thus, we can see that in the case of the flight controller scheduling problem, steps 1 and 3 of Ernst's framework are not required. The remaining four steps provide a reasonable framework for the problems that require solving for FOD console scheduling.

Bailey's [**7**] 1985 study in *Computers and Industrial Engineering* describes the scheduling problem as only a two-step problem: the shift scheduling problem[1] (Ernst's step 1, 2, and 3) and the days off scheduling problem (Ernst's step 4 and 6). Whereas Caprara's [**8**] 2003 study in *Mathematical Programming* describes a different two-step problem: "...the definition of the sequence of working and rest periods (called *pattern*) for each employee, and the definition of the daily assignment to be performed in each working period by each employee." Caprara's decomposition approximates Ernst's steps 2, 3, 4 and 6 first and step 5 second. From these examples, we see that there is some variation in the definition of the steps involved as well as disagreement about the proper order in which the steps should be addressed. Ernst's breakdown is the most robust definition found in this review, inclusive of all the possible steps found in other works.

Choi [**9**] tackles a scheduling problem at a busy restaurant in downtown Seoul, South Korea. Choi's concern is to develop a new model that will account for changing demand and daily shift length while also providing a balance between [**10**] full-time and part-time employees (Ernst's steps 1, 3, and 5). Choi develops an integer programming solution to achieve these goals while minimizing cost within overstaffing and

[1] Bailey's choice to use the phrase "shift scheduling" for a combination of steps 1-3 when Ernst uses the phrase to refer to step 3 alone can cause confusion. The phrase "shift scheduling" should be used carefully.

understaffing constraints. Choi’s result is a set of lines of work showing days on and off for a number of full and part-time employees. Therefore, Choi’s study presents a solution that accounts for Ernst’s steps 1-5. Step 6, or staff assignment, is not addressed.

The omission of step 5 by Bailey, step 6 by Choi, and step 1 by Caprara is typical of many of the studies reviewed. The majority of research on this topic focuses on a particular subset of the steps required to deliver a full staff schedule solution. Most researchers seem concerned with the optimization of Ernst’s steps 2 through 4. The mathematical optimization of the set covering problem itself provides wide latitude to experiment with different optimization techniques and strategies. For large formulations of the problem, significant time can be spent on these two steps if a manual solution is employed. This is a major barrier to efficiency for constant operations workforces that must complete a staff schedule on a regular recurring basis. Therefore, optimizing this part of the problem can provide significant time and cost savings for the scheduler.

A wide array of computational methods has been applied to attempt to optimize steps in the staff scheduling problem. Some techniques encountered in this review include greedy algorithms, branch-and-bound, branch-and-price, tabu-search, goal programming, constraint programming, local search, genetic algorithms, memetic algorithms, and fuzzy set theory. These methods all share in common that they are different types of linear programming (LP) or integer linear programming (ILP). Of 22 works related to staff scheduling reviewed in this study, 16 of them were attempts to develop a new linear programming model for a staff scheduling problem. Three others were surveys of other published works. Only the remaining three works addressed anything else other than a new LP model.

In the first of these works, Rocha [**11**] demonstrates the flexibility of a simple mixed integer programming model to many types of scheduling problems. After applying her model to two real-world cases, Rocha demonstrates that it can also apply to a large set of benchmarking datasets available in the literature. Through her discussion, Rocha discusses the practical steps required to modify an ILP model for different workforce constraints, planning period lengths, sub-cycle durations, and cyclic pattern restrictions. In so doing, Rocha provides one of the most practical models reviewed; and one of a very few number of studies that addresses choices with regard to these input constraints in addition to the mathematical model. Still, Rocha leaves some questions unanswered, such as how to resolve constraints against preferences, or even how to address the health implications of shift work on the scheduling problem.

Baker's 1977 article in *Management Science* [**12**] provides an arithmetic model for staff scheduling problems that does not require ILP. While Baker's formulation is easy to understand and quick to apply, it is mostly limited to the "days off" problem (Ernst's step 2). A notable point in both Rocha's and Baker's work is that they both provide a simple formula for calculating the required workforce; a feature not addressed in many other studies.

The third unique work reviewed is Laporte's brief summary in *The Journal of Operational Research Society* [**13**], in which he describes his techniques for developing rotating schedule solutions without employing any ILP. Instead, Laporte shares his arithmetic and manual processes for addressing the entire staff scheduling problem. Laporte also summarizes some of the most common constraints encountered during his years of consultation on staff scheduling problems, including those related to night shifts.

Laporte uses simple arithmetic rules which allow him to solve any rotating schedule problem by hand quite effectively. Advantages to this technique are that it allows for experimentation and development of multiple options for the customer or decision maker to select from. There are important downsides to the technique. The first is that it requires the customer to commit to a rotating schedule style. The second is that Laporte does not account for applying a cost function. Laporte's measure of success is that he has satisfied his customer's initial constraints and that his customer is able to select a schedule option they find satisfactory.

Laporte's work is the most analogous research to the schedule design techniques used by NASA's flight controller groups. The weekly rotations used by NASA FOD can be easily expressed in Laporte's style. Figure 13 shows the existing ADCO weekly rotation, first shown in Figure 5, expressed in Laporte's style as two options for a multi-team.

Week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	X	X	X	X	N	N	N
2	N	N	N	N	X	X	X
3	D	D	X	X	A	A	A
4	A	A	A	A	X	X	X
5	X	X	D	D	D	D	D

Week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
1	N	N	N	N	X	X	X
2	D	D	X	X	X	X	X
3	A	A	A	A	X	X	X
4	X	X	X	X	X	D	D
5	X	X	X	X	A	A	A
6	X	X	X	X	N	N	N
7	X	X	D	D	D	X	X

Figure 13 – Two rotation schedule options for ADCO

However, Laporte's solution assumes a rotating schedule in which each row denotes a week in a continuous cyclic pattern. Team 1 works the week 1 pattern, then the week 2 pattern, and so on. In this way, the ADCO console could theoretically be staffed by as few as 5 operators using the 5-team rotation in Figure 13. The 5-team rotation would require an average of less than 38 hours a week ((21 shifts*9 hours)/5 teams).

Unfortunately, the 5-team option is not implementing the legacy ADCO 7-block rotation as intended, as the night shifts and afternoon shifts are each worked in a continuous 7-day set (week 1 into week 2 and week 3 into week 4). In order to effectively implement the weekly rotation, a minimum of 7 teams are required to provide days off between shift blocks. In the 7-team option, the console team works an average of 27 hours per week - too few to be considered on console full time. It is clear that the current weekly shift rotations used in FOD do not translate well to this type of schedule design.

Another deficiency in Laporte's solution is that of flexibility. While his solutions are elegant, complete, and minimize the workforce, they do not allow any input from operators to pick their preferred shifts. In the 5-team option above, all operators would be required to work every other weekend for the duration that the cycle repeats, regardless of specific date. Laporte presents techniques such as the use of relief teams and overlapping schedules in order to add more flexibility to the method.

However, the most serious flaw to Laporte's method is the number of manual iterations that will be required in highly constrained cases. Manual solutions suffer from the "cascade problem" (example in Appendix D) in which small changes to the solution require a cascade of other manual changes in order to find a new schedule that will meet all constraints. The cascade problem is exactly why the literature has been so focused on the use of ILP for large formulations of the staff scheduling problem.

Eitzen [**14**] shows the benefits of ILP in his case study of rostering at a power station in Australia. Eitzen's method involves enumerating many options for tours of duty and then selecting for each employee via various integer programming methods (he compares column expansion, branch-and-bound, and column subset methods). Eitzen is able to accommodate more constraints than shown by Laporte, including equity constraints between operators as well as an overall cost score.

The methods employed by Eitzen are similar to many other optimization methods in the literature and have proven quite robust (especially when combined with heuristic methods, see Kassa [**15**] and Silva Rocha). However, as applied by Eitzen, the model does not account for constructing a rotating schedule over a sub-period of the schedule, as in Laporte. Nor does Eitzen consider any specific operator shift preferences.

As Ernst points out in his survey, the best performing systems that converge on an optimal solution tend to be combinatorial methods that use constraint programming and branch and bound-type linear integer programming. This is in fact how Eitzen was able to find various optimal solutions to his Australian power plant problem. Silva Rocha concludes in his research that the best performing systems use a combination of ILP and heuristic methods to find a good but not necessarily optimal solution. For example, when Silva Rocha looked at rosters with large data sets (dozens of employees with dozens of tasks to fill over a long planning horizon) the ILP solution often would take hours to compute while the heuristic methods had no difference in solution time from the simple data sets.

The application of linear programming to the staff scheduling problem began with Dantzig's original article in 1954. In his analysis, Dantzig describes a process by which the objective function, the total number of toll booth operators required to operate all open toll booths, is minimized by filling in half-hour blocks on a continuous schedule. This general concept of assigning independent tours of duty to each employee and then to look at the surplus or shortage during each block of time, is the approach used in most scheduling problems since Dantzig. For example, a paper entitled "Operator Scheduling" from 1979 by Keith [**16**] describes an ILP method for scheduling telephone operators at the Illinois Bell Telephone Company. The schedule is broken down into quarter-hour blocks that must be filled and the objective function is the shortage of operators in each block of time. In both of these examples, the minimization of the objective function and creation of tours of duty accomplishes steps 2-5 in Ernst's framework in a single step.

Combining multiple steps of Ernst's framework - especially the steps of days of scheduling, shift scheduling, and line of work construction - tour scheduling - is more common than deconstructing the problem into the individual steps as identified by Ernst.

The tour scheduling approach allows for a top-down solution. In bottom-up solutions - in which each of Ernst’s steps are addressed sequentially - decisions made in the days off scheduling step may over-constrain later steps, and so on. This is the case for Laporte’s framework discussed above, which can easily become over-constrained.

Silva Rocha offers a general model of a top-down ILP solution. The model provides a circular line of work unique to each individual in the workforce (operator or team). Silva Rocha demonstrates his model by applying it to several case studies. By employing heuristic methods, Silva Rocha demonstrates improved efficiency while generating valid schedules. His heuristics involve simple algorithms for checking inputs against each other to verify feasibility. For instance, the constraint on minimum days off is compared to the number of teams and the planning horizon to compute if sufficient days off are even available.

This type of advanced heuristic is the clear state-of-the-art in research on the staff scheduling problem. Other researchers such as Leksakul [**17**] have applied a genetic algorithm heuristic to the problem. Greedy algorithms are also popular, as used by Choy to demonstrate an optimal solution to a nurse scheduling problem. Lastly, as discussed above, Laporte uses his own experience providing schedule design to commercial customers to argue that pure ILP solutions are too rigid and that “rules must be broken.” In other words, some heuristics should be applied to find truly efficient solutions.

This review found a clear consensus in the literature towards considering the staff scheduling problem according to Ernst’s framework, with top-down solutions using ILP and heuristic methods that focus on the tour scheduling step of the problem. A wide array of specific mathematical techniques in this area have been developed, from those described above to even more innovative approaches such as the genetic algorithms applied by Leksukal and Carrasco [**18**] to the greedy algorithms applied by Choy. A researcher seeking to improve these solutions even further would be refining these already advanced mathematical techniques, which are out of the scope of research for this author.

However, a separate clear theme was found in the review. While a surprising array of optimization techniques are provided for applying scheduling constraints to common staff scheduling problems, the existing research provides little to no discussion of the development of these constraints. One of Silva Rocha's many case studies serves as an example. Silva Rocha's provides a 4-team solution for employees working 24/7 shifts in a glass factory. In this case, Silva Rocha's optimal solution involves a backwards shift rotation; employees in the glass factory would first work a set of night shifts followed by a day off, then a set of afternoon shifts with a day off, and finally a set of day shifts. The pattern ends with two days off before the pattern begins again. In Silva Rocha's discussion of this problem he states that the days off constraints were givens and not derived. He provides no discussion of the relative choice to shift backwards as opposed to forwards - a forward rotation potentially being easier for employees to adjust their circadian clock.

Occupational Health

The effects of shift work on worker fatigue and sleep patterns has been studied extensively in occupational health journals. In two separate reviews, Akerstedt and coauthors discuss the impacts on sleep due to shift work. Akerstedt reviews studies on disturbed sleep in his first article [**19**]. Akerstedt's second review covers sleep loss and fatigue [**20**]. Different work patterns have been studied along with their speed of rotation. Due to the average circadian clock being longer than 24 hours, as found by Czeisler [**21**], there is evidence that a forward (or clockwise) shift rotation allows easier adaptation. In an article titled *Rotating Shift Work Schedules That Disrupt Sleep Are Improved by*

Applying Circadian Principles [**22**] Czeisler presents data to reinforce the recommendation that a "phase delay" (forward rotation) is probably better for adaptation than a "phase advance" (backwards rotation).

As discussed in Akerstedt's review the occupational health research has shown that shift work, especially night shift work, has acute effects on the health of employees. These acute effects are quantified as Shift Work Sleep Disorder (SWSD) and are found in at least 10% of shift workers [**23**]. A related area of study is the incidence of accidents, mishaps, and injuries during shift work. Several studies were reviewed on this topic. Folkard's 2006 review of an array of published studies [**24**] provides a starting point for understanding the impact of shift work on risk in the workplace. Folkard finds evidence of increased risk on afternoon and night shifts compared to day shifts (over 20% increase) as well as evidence of increased risk on subsequent night shifts in a shift set (at least 30% increase by the 4th shift).

Little data is available regarding the increased risk of longer than four consecutive night shifts, as it is an uncommon practice, despite the frequent use of 7-day stretches of night shifts in flight controller schedules. In fact, a European Parliament Directive on night work (Directive 2003/88/EC) limits night workers to 48 working hours in a seven-day period with at least one 24-hour rest period. Similar best practices found across many industries made it difficult to find an analog for NASA's longer night shift blocks.

Despite the significance of the research regarding shift work, little to no discussion of designing rotating shift schedules to minimize these effects, as recommended by Akerstedt, is found in the staff scheduling optimization field. Furthermore, the staff scheduling optimization research suffers from a general assumption that the constraints provided by the customers are reasonable and should be implemented as given. In the literature reviewed, there was no discussion of techniques for evaluating given constraints. The consensus in this field on how to evaluate a good schedule seems to follow three criteria: schedule is complete, meets constraints, and was generated quickly.

Spaceflight Studies

Some limited studies on the shift work of spacecraft flight controllers have been conducted, starting during the Space Shuttle Program in the 1990s. This review identified four such studies, all of which focused on the sleep effects of shift work. None of them addressed the design of the flight controller staff schedule specifically.

The first study, conducted in 1992 during the STS-53 space shuttle mission by Kelly et al. [**25**], collected data on a small set of flight controllers in Houston to assess the effects of high performance shift work on their sleep patterns and performance. The data showed a strong correlation between extended shift work and degradation in some factors - especially loss of sleep and motivation on the night shift. The second study, also conducted in 1992 across a handful of space shuttle missions by Stewart et al. [**26**], investigated the usefulness of light treatment on flight controllers supporting from the Payload Operations Control Center (POCC) at the Marshall Space Flight Center (MSFC) in Huntsville, Alabama. The study made no recommendations on the design of shift work patterns, but did demonstrate clear benefits of light treatment for night shift workers. Measures of alertness and effectiveness were improved while negative effects such as fatigue and sleep quality were reduced.

The third and fourth study on NASA flight controllers are more modern studies conducted on International Space Station (ISS) flight controllers. The first, known within the halls of MCC as “the Harvard Sleep Study,” was conducted over a lengthy period in 2011 and 2012. The study sought to implement the knowledge of researchers from Harvard Medical School to employ best practices and interventions to improve the sleep and effectiveness of ISS flight controllers in Houston. The study both collected sleep data on the subjects and recommended interventions, such as light treatment, sleep patterns, and modifications to shift activities. Unfortunately, while some informal literature is available on what interventions were employed at the time, no published peer-reviewed studies are available on the results of the interventions.

The final sleep study was conducted on ISS flight controllers working for the Japan Aerospace Exploration Agency (JAXA) [**27**]. The observational study observed the sleep patterns of a limited number of volunteers who supported a mix of shift work and office. Data was collected both via surveys and also via antigraphic devices worn on the wrist. The data showed strong correlations between night shift work and many negative sleep effects. This study addressed the prevalence of Shift Work Sleep Disorder (SWSD) in flight controllers and provided very suggestive results that flight controllers should be reviewed for SWSD. Furthermore, the data suggested that shift patterns should be designed to minimize the effects on individuals with SWSD.

These four studies represent the only known research into shift work involving 24/7 human spaceflight operations. The limited research beyond a handful of sleep studies represents an opportunity for further research and possible drastic improvement over current practices. Additionally, while the interventions and recommendations from these sleep studies indicate promising results, in the years since the studies there has been little to no formal adoption of evidence-based sleep interventions across the workforce.

Summary of Literature Review

The field of staff scheduling research has a long history of developing faster and more adaptable optimization techniques. Further advancement in this area is left to the mathematicians. The least explored areas of research involve the synthesis of these optimization techniques with other areas of study such as occupational health, sleep effects, and circadian rhythms. The review also revealed the absence of any complete suggested framework beyond Ernst's 6-step scheduling process. The well-refined concepts of systems engineering and cradle-to-grave design have not been combined with the scheduling design recommendations to provide a framework for designing a new staff schedule from scratch. Features common to all engineering design processes - stakeholder analysis, requirements specifications, performance tracking, and system maintenance - could be applied to staff scheduling solutions to ensure high quality schedules are developed which meet the needs of all stakeholders.

In addition to the opportunity to provide synthesis between the worlds of staff scheduling, occupational health, and systems engineering, there is also an opportunity to apply any and all of these existing fields of study to the staff scheduling processes of NASA's 24/7 flight control organizations. None of the above discussed techniques are currently being applied by FOD for flight controller console scheduling, other than some limited best practices related to sleep health. FOD managers can leverage the advancement in several areas of academic research - especially staff scheduling optimization techniques and up-to-date recommendations for occupational health - to improve the efficiency of their scheduling processes while meeting the interests of their stakeholders. However, many unique features of the flight controller scheduling problem limit the ability to "plug-and-play" any existing optimization techniques. These features include:

- Shift work comprises only a fraction of a flight controller's workload
- A flight controller will often report for office work the day before/after shift work
- Number of operators is large
- Cyclic schedules are impractical due to the large numbers
- Operators must meet "proficiency" requirements

- Many operators are more “useful” to the organization in office work tasks
- Strong stakeholder interest in inequity between junior and senior operators
- Workforce planning is not influenced by the console schedule

Most of these features were not found in any of the staff scheduling research reviewed. The most impactful feature that prevents the use of existing techniques is the large number of operators who must be scheduled for console shifts within the proficiency requirements. Most staff scheduling research focuses on providing optimal schedules that meet days off constraints with the fewest possible numbers of teams or operators. More efficient schedules allow managers to reduce workforce size and save money. However, due to the quantity of non-shift work tasks that must also be supported by each flight controller group, workforce planning in FOD is largely agnostic to the console schedule rotation.

A related issue is that these non-shift work tasks change the nature of “days off” in the console schedule. A day off from shift work does not always mean a day off for the employee. In fact, quite often flight controllers will report to work for standard office work on any weekday they are not scheduled for, regardless of the console schedule. For example, a flight controller assigned to work through the weekend will often not take a “day off” before or after the weekend. This changes the nature of how days off constraints apply to schedule design.

The unique features of the flight controller scheduling problem make it an excellent candidate for developing new techniques for the staff scheduling problem. Application of ILP techniques to model a flight controller schedule will result in measurable improvements to the completeness of schedules and employee satisfaction. Techniques developed for this problem can then be applied to other analogous work environments that share some of the unique features of the flight controller scheduling problem. Additionally, concepts for stakeholder analysis, specifying requirements, benchmarking, and other methods of feedback can be applied, thus bringing a systems engineering design process into this field.

CHAPTER III:

FRAMEWORK

Theory

The literature review has revealed an entire field of research into staff scheduling problems that can be applied to the flight controller scheduling problem outlined above in the background section. Several key concepts, tools, and solutions can be applied to help improve the efficiency and success of console operations in the MCC.

Additionally, much of the reviewed research ignores certain important real-life impacts of the standard staff scheduling solutions. Occupational health research and research into computational solutions to staff scheduling problems are studied independently with little overlap.

The theory section will propose a unified framework that combines all of these disparate fields of study into a single scheduling process. This process proposal will incorporate the best practices of the staff scheduling literature, the occupational literature, and the experiences of the Flight Operations Directorate (FOD) at NASA. The proposed framework will be proposed in generic terms that can be applied to any analogous 24/7 operator scheduling problem. However, references to the flight controller scheduling problem will be used as examples to bound the possible design options.

Thesis statement

Combining the best practices from the existing research on staff scheduling problems with a Systems Engineering approach will facilitate the design and implementation of an integrated solution. This approach will result in measurable improvements in efficiency, employee satisfaction, and constraint completion. Currently, neither of these two frameworks are applied to the specific staff schedule found amongst the strategies used to schedule NASA FOD flight controllers.

Proposed Framework

Ernst's framework is widely cited as the ideal framework for the staff scheduling problem. Therefore, the theory for how best to establish an integrated solution to any staff scheduling problem starts with Ernst's framework:

1. Demand modeling
2. Days off scheduling
3. Shift scheduling
4. Line of work construction
5. Task assignment
6. Staff assignment

This six-step process must be integrated with the concepts of systems engineering. The waterfall process model presented above, can be summarized as a six-step process:

1. Requirements analysis
2. Specifications
3. Design
4. Implementation
5. Test
6. Maintenance

The six steps of Ernst's staff scheduling solution process amount to the design of the schedule itself, and thus fall within the design cycle of the systems engineering process. Therefore, an integrated process would be as shown below (with notes explaining applicability to a staff scheduling problem):

1. Requirements analysis (stakeholder analysis)
2. Specifications (define measurable performance measures)
3. Workforce Planning

4. Design (select how each of the following will be done)
    a. Demand modeling
    b. Days off scheduling
    c. Shift scheduling
    d. Line of work construction
    e. Task assignment
    f. Staff assignment (shifts and on-calls)
5. Implementation (create a schedule with above design)
6. Test (try out the schedule for a cycle)
7. Maintenance (incorporate feedback or other updates)

Note that the intent of the waterfall model is to provide feedback between each step in the process as it proceeds. The design should be iterated throughout the process either due to new information or the results of implementation and testing. Additionally, implementation or test results may require a new stakeholder analysis and new design specifications, in some cases.

Requirements Analysis

If applying this new framework to an existing staff scheduling process, the currently applied requirements must be identified through a thorough stakeholder analysis. A successful stakeholder analysis should include identification of all stakeholders and the top interests of each, even the less important stakeholders. The current requirements should be compared to the stakeholder interests to evaluate if the current requirements are actually meeting stakeholder needs. Stakeholder interests should be ranked and compared to help identify the top design considerations. Based on the stakeholder analysis, new requirements should be identified. Requirements should be measurable and should measure outcomes that can be affected by the schedule design. Some requirements that might be used include:

- Efficiency of scheduling process
- Deadlines for schedule completion
- Number of operators required
- Over/under-staffing
- Number of constraints/guidelines met
- Cost (must specify cost function)
- Perceived fairness of schedule
- Number of hours worked per week
- Person-hours required to complete scheduling

Note that “cost” could literally refer to the cost of the schedule (dollars per hour) or could represent some other minimization function. For example, as will be seen below in the design for the flight controller scheduling problem, a cost function was developed to represent the availability of the most senior operators for other tasks.

Specifications

Specifications generically refer to the overall design specifications of an engineered system. In this case it needs to include both the specific values for the requirements or technical performance measures (TPMs) we selected for our schedule at the end of the requirements analysis. The specifications should be vetted by the stakeholders to get concurrence that the intent of their needs are met. Any feedback from stakeholders on specifications should be compared to the data in the needs table to ensure the feedback is in line with the high priority needs that were identified for each stakeholder. If there is disagreement, the needs assessment, the requirements, or the specifications will need to be iterated.

For most engineered systems, especially when engineering a widget, the design specifications will refer to measurable parameters of the physical design: size, speed, efficiency, noise level, safety, durability, reliability, maintainability, etc. However, in the case of designing a staff scheduling solution for a customer, what is being engineered is the process to create the schedule. Therefore, the specifications should relate to that process as well as outcome. For example, the efficiency of the process (person-hours required) could be specified. Other process specifications might include a requirement that operator preferences are taken into account.

If applying this new framework to an existing staff scheduling process, then it may be necessary to specify requirements that preserve existing features of the process of record. For example, the length of the schedule period or the cycling sub-period may need to be fixed at the previous values. In the case of the flight controller scheduling problem, the stakeholder analysis showed that the majority of flight controllers would not be comfortable with a rotating schedule in which they work multiple types of shifts in a given assigned tour. Instead, flight controllers expect to be assigned a single block of shifts of one type on each week that they are assigned, and that the shift blocks are the same length each week.

Therefore, there will be a specification that the schedule sub-period will repeat weekly with a fixed pattern of tours for each shift type (night, day, afternoon). There is no literature on the staff scheduling problem that shows this particular requirement is necessary or superior to other solutions. However, it is being implemented in order to minimize the number of changes to the staff scheduling process in the first iteration - hopefully maintaining operator satisfaction and a willingness to try out other new features of the process.

Workforce Planning

The design choices that will be made in the following steps are heavily dependent upon the size of the workforce that is available to be scheduled. Conversely, there may be specifications that impact workforce size, such as a requirement for a minimum or maximum number of shifts over a schedule period. In the case of the flight controller scheduling in NASA FOD, the operators are expected to spend more than 50% of their full-time work hours on tasks other than staffing the console. Therefore, FOD has a requirement for a larger workforce number than if nearly 100% of all operators work hours were devoted to console support.

Shift schedule designers should ensure that workforce planning is an included step in their process. Different workforce planning strategies will need to be employed depending on the application. For staff scheduling problems with a simpler tasking - wherein the shift work is the only duty - workforce planning will be directly related to demand modeling (discussed below). In such cases, demand modeling and workforce planning steps may need to be conducted simultaneously. In other cases workforce planning will be related to budget or the supply of skilled workers in the employment market.

No specific discussion of detailed workforce planning is presented here due to the workforce size of the flight controller scheduling problem being a given number. The theory of an engineered staff scheduling design process simply requires that workforce planning be considered.

Occupational Health

Review of published literature regarding circadian effects of shift work and night work suggests that design of a 24/7 staff schedule should consider the state of the art of sleep science from occupational health journals. Several basic recommendations can be gleaned from an initial review. In particular, the articles from Akerstedt and Czeisler discussed in the Literature Review above provide the following starting constraints for any 24/7 schedule design:

- Shift rotation should always rotate forward (phase delay)
- Health effects can only be minimized by minimizing night shifts
- Screening employees for SWSD can improve outcomes
- Light treatment can improve outcomes and performance
- Schedules should allocate sufficient adjustment time for night work

Also discussed above were Folkard's results regarding the risk of errors on night shifts. Folkard showed that increased risk effects persist even beyond an adjustment phase. This impact was checked against available flight controller "command error" data. The command error database contains information on operational errors made by International Space Station flight controllers and contains over 1,800 records from two decades of operations.

Data was available from the command error database for the shift of error occurrence (night, day, or afternoon) and the number of consecutive days at work when the error occurred. A summary of this data is shown in Figure 14. Note that approximately 372 of the 1830 records had null values for either shift occurrence or consecutive days. These errors were not included in the below results.

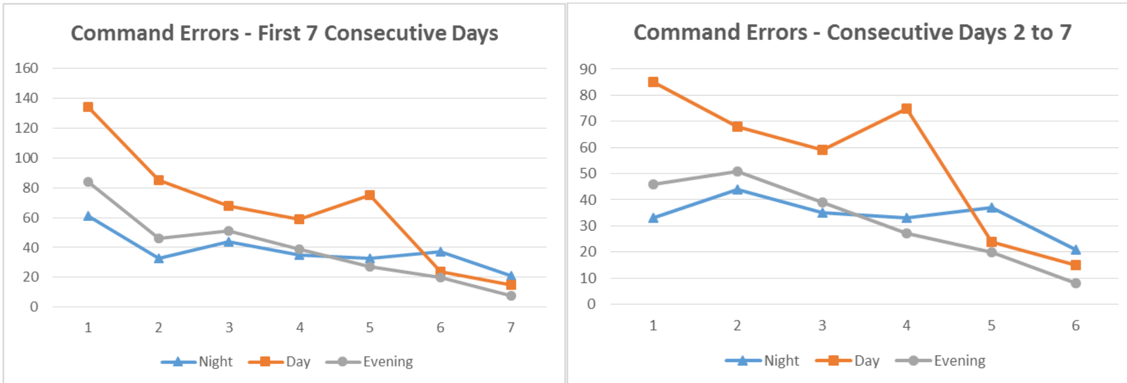


Figure 14 – Command error data

This data has three notable features. First, there is a clear “first day at work” effect resulting in the highest number of errors occurring on the first day at work for all shifts. Second is the relative number of errors on the day shift is the highest. Data on total commands sent was not reviewed. Therefore, no conclusions can be drawn regarding the percentage of errors to commands sent on any particular shift.

The third and most pertinent feature is the trend over the seven consecutive days. Note that errors were reported for consecutive days at work as high as 13. However, given that no ISS shift schedules ever deliberately schedule operators for more than 7 days in a row, the review of the data was limited to that time horizon. For the data reported up through seven consecutive days on console, there is downward trend in all datasets. However, when all seven days are considered the slope of the errors on the night shifts is only 36% as steep as the afternoon shift and 25% as steep as the night shift. When the first day is omitted the slope of errors on the night shift is only 25% as steep as the afternoon shift and 15% as steep as the day shift.

This data appears to be consistent with Folkard and other researchers have found a sustained elevated risk of error on night shifts. While more research is required, it seems safe to assume that any effects of consistency of operations that reduce errors on consecutive shifts are significantly reduced on the night shift. Therefore, in the interest of reducing errors and improving flight controller health, shorter rather than longer shift blocks will likely result in improved outcomes.

Designers of 24/7 staff schedules can benefit from the long history of occupational health research. Designers should at minimum acknowledge the effects of night shift work that are imparted on operators by their schedules. Ideally, their designs should take sleep effects into consideration and design to minimize negative impacts of night shift work.

Options for Schedule Design

The sections below outline the general theory of the different options for each stage of the scheduling process design, following Ernst's decomposition. Each stage of the schedule design process presents the decision maker with options related to the scheduling style or method of deriving the solution. These decisions should be based on the particular needs of the application, as identified in the requirements and stakeholder analysis already conducted. It is important to note that often the decision made in one step of the design process will dictate the method chosen in another step. For example, if it is desirable to leave the employee some choice in their work schedule during the staff scheduling phase, then it is not possible during the line of work construction to build schedules specific to individual employee's needs.

There are several possible contradictions such as this found within the design process. Therefore, it is imperative that a scheduler be flexible and be willing to iterate during the design phase. If a guideline or high priority stakeholder need dictates a particular design decision, then the scheduler needs to be willing to readdress earlier phases of the design to accommodate the requirement into the rest of the design.

Demand Modeling

Demand is broken down into three types, per Ernst: flexible, task-based, and shift-based. Task-based and shift-based demand require minimal modeling to forecast for the scheduling period, as it is a known or set number based on the requirements of the job. For example, in the MCC, flight controller must staff the console per shift-based demand, with one flight controller assigned for each of the three shifts every day. In cases where support personnel are required, some days or shifts may require an extra flight controller to support in the MPSR role. A common shift-based demand model for a FCR flight controller and their MPSR position is represented in Figure 15.

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
Morning	1	1	1	1	1	1	1
Afternoon	1	2	2	2	2	2	1
Night	1	1	1	1	1	1	1

Figure 15 – Shift-based demand

The demand model in Figure 15 can also be described as a workload matrix. An evenly distributed workload matrix is often only found in cases of shift-based demand. In task-based demand, the demand may be uneven over a given day or even a given shift due to the tasks that need to be accomplished. In other words, rather than having a set number of shifts each day, as in shift-based demand, there is fluctuating demand for operators to complete specific tasks throughout a shift, day, or other sub-period.

Period	1	2	3	4	5	6	7	8	9	10
Task A Demand	1	2	1	2	3	3	2	2	1	1
Task B Demand	0	1	1	1	2	2	2	1	2	1
Total Demand	2	3	2	3	5	5	4	3	3	2
Person A										
Person B										
Person C										
Person D										
Person E										
Person F										
Person G										

Figure 16 – Task-based demand

An example of task-based demand is illustrated in Figure 16. Task A and Task B must be completed throughout a day divided into 10 segments at varying demand. Employees are assigned in shifts of 5 segments in overlapping shifts to meet demand. The total demand is met by assigning 7 employees to shifts during the period. This results in some overstaffing (such as during segment 6, 8, and 9). Effective solutions for task-based demand problems seek to minimize both over and understaffing costs in order to find an optimal solution.

The last type of demand is flexible demand. Flexible demand refers to demand that cannot be accurately forecast or predicted, usually due to the source of demand being external. Flexible demand is most common in the service industry, where the influx of customers or patrons is not known ahead of time. In these cases, demand must be estimated based on prior experience. Additionally, the cost impact of over or understaffing for any given schedule must also be estimated, as the accuracy of the schedule compared to demand will not be known until the schedule implemented. An effective approach to flexible demand is to construct a model of the demand function based on prior data. Queuing theory can be used to model flexible demand.

Tour Scheduling

Steps 2, 3, and 4 of Ernst's decomposition are the steps most heavily discussed in the literature. In much of the research, these steps have been combined into one or two sub-steps in order to find an ideal optimization. Combining either days off, shift, or line of work scheduling into a single step is often referred to as tour scheduling. Below, the theory of each of these steps when not combined will be reviewed.

Per Ernst, days off scheduling "...involves a determination of how rest days are to be interspersed between work days for different lines of work." This determination will often be based on requirements or constraints identified during the prior analysis step. If days off are specified by union contracts or hard constraints, days off scheduling may be a simple statement of constraint such as “two days a week” or “every other weekend.” If the days off requirements are more flexible, then the design of days off may need to be combined with line of work scheduling in a tour scheduling step. Most of the solutions reviewed for this study completed the days off scheduling step by implementing days off constraints as part of a tour scheduling optimization problem.

Per Ernst, shift scheduling “...deals with the problem of selection, from a potentially large pool of candidates, what shifts are to be worked…” Ernst is specifically referring to the times of day and length of each shift. The reference to a large pool of options is applicable to cases such as service personnel, who might work shifts of varying lengths that can start at half-hour intervals throughout the day. The number of options will be more limited in operational environments with more rigid constraints. In the most rigid applications, such as a power plant with two 12-hour shifts or the three 8-hour shifts in mission control, the step of shift scheduling may be skipped, as the shifts are known and never change.

Ernst describes line of work construction as “...the determination of a sequence of duties spanning some longer period of time.” The line of work is the actual shift schedule, or sequence of days off and work shifts built around the decisions made in steps 2 and 3. The design of lines of work depends on various input constraints and stakeholder interests. Ernst identifies two options for this step that will significantly impact the design. A cyclic line of work design results in all operators having the same line of work but with a delay to the schedule applied to each subsequent operator. Examples of a cyclic schedule design as described by Laporte were discussed in the literature review. Ernst’s second line of work model is acyclic but involves the definition of “stints.” Ernst’s stints are analogous to the “shift blocks” in flight controller console scheduling, discussed above in the Background section. Stints are defined as a set of shifts between days off which are always worked together.

The evolution of staff scheduling research has largely merged these three steps into the process of tour scheduling. Rather than perform days off scheduling, shift scheduling, and line of work construction as a serial sequence of steps, the prevailing theory is that a process that accounts for all related constraints in a single optimization step is most efficient. Constraints for days off or the design of stints accomplish the intent of the days off and shift scheduling steps. These constraints should then be used as inputs to an optimization algorithm - most commonly some type of linear programming solver - to produce a single top down solution that meets all constraints.

Task Assignment

Tasks, in the context of Ernst's six-step process for staff scheduling, refer to particular duties required on each shift in the repeating schedule. Some tasks will require more senior operators and will have restrictions on staffing. Therefore, task assignment is the step in which the restrictions on the schedule, based on the tasking for each shift, which dictate which type of operators can work that shift.

Application of the task assignment will generally take the form of restrictions on the constructed lines of work. In practice, this restriction can be applied either before or after the lines of work are constructed in the previous tour scheduling step.

If the restrictions are put in place before tour scheduling, then task assignment will take the form of constraints on the tour scheduling process. For example, consider a particular staffing problem has 10 operators but only 5 are senior while the other 5 cannot perform senior tasks. A constraint can be applied to line of work construction that ensures that only 5 of the 10 lines of work require senior operators.

If the restrictions are put in place after tour scheduling, then in order to complete task assignment, the completed lines of work will need to be categorized based on their tasks. Lines of work that contain shifts with tasks for senior operators must be categorized as lines of work that can only be assigned to available senior operators, and so on.

This second method is prone to error, as there is a risk that all lines of work could end up with at least one shift that requires a senior operator. Therefore, the most effective application of task assignment is to design constraints into the tour scheduling process that ensure lines of work are designed that accomplish all tasks while leaving options to assign operators at all seniority levels.

Staff Assignment

Staff assignment is the final step of building the staff schedule. Once lines of work have been properly designed through the first 5 steps of Ernst's process, the individual operators who make up the workforce must be assigned each to a line of work. Similarly to task assignment, it is possible to accomplish staff assignment after lines of work are completed (the linear method suggested by Ernst's 6 steps) or in process during the tour scheduling step.

If staff assignment is accomplished after lines of work are constructed, then it is possible to provide choice or options to the decision makers or to the operators themselves. Operators can provide selections or preferences for which line of work they prefer. A ranking system can be designed to then fairly assign the lines of work to each operator. For example, a common practice in the airline industry is for pilots to submit their flight choices each month. The pilot preferences are then used to assign each pilot a set of routes for the schedule period, based on seniority.

If staff assignment is combined with tour scheduling, then personalized constraints can be taken into consideration in the line of work construction. Operators can submit different preferences, such as time of day or day of week preferences, and those inputs can be considered against the other constraints that must be met during tour scheduling. For example, two operators who prefer Sundays and Tuesdays off respectively, can be assigned lines of work that meet these preferences. However, combining staff assignment with tour scheduling presents challenges by limiting choice. If an ILP solution is used to create complete schedule for all operators, all shifts may be assigned automatically with no selection possible. Alternatively, to allow choice in the process would require bottom-up shift selection, preventing the benefits of a top-down solution such as the use of ILP optimization.

Due to the downsides of combining staff assignment with tour scheduling, performing staff assignment as the final step in the process is the most likely method to meet all stakeholder interests, including operator preferences.

Implementation

Show that the design can be used in practice by creating a schedule, either on a test case or the real team assets. Implementation should always involve taking notes/data on issues that arise or changes that are made. This allows for effective operation of the test phase and feedback into the design if iteration is needed.

Test

Test final design against specifications and constraints by applying design to a real or test case and gathering data to compare against specifications. All specifications determined from the analysis phase should be measurable, such that the stakeholders can make an objective determination as to whether the design is meeting specifications.

Maintenance

The solution methods should use tools and techniques that can be passed on to other employees for future scheduling cycles. If the algorithm or other tools cannot be updated or reused then the new method will likely not survive the turnover of the scheduling team.

Methods

Overview of Methods

NASA FOD flight controller scheduling is a staff scheduling process that has been implemented in its current form for over a decade. Therefore, any recommended changes to the process had to be carefully selected. New methods needed to result in measurable improvements to the stakeholder interests, while preserving as many features of the current scheduling process as possible. Preservation of the status quo was desired in order to ensure acceptance by stakeholders of any proposed process changes.

The study identified, through the requirements analysis below, that measurable improvements could be made in the process design specifications through changes to three steps in the staff scheduling process used in the ADCO group. These steps will be referred to as *Schedule Rotation, Line of Work Construction,* and *Staff Assignment*. These three steps encompass all of the six phases of the staff scheduling defined framework, as outlined by Ernst, with the exception of demand modeling.

Several features of the scheduling process in the ADCO group were not addressed, in order to preserve key features of the status quo process. The scheduling period was kept at a 13-week quarterly length, with a repeating weekly shift rotation. Operators will continue to only be required to work one type of shift between breaks - rotating schedules in which operators follow a progression from day shift to afternoon shift to night shift were not evaluated. The merits of these types of schedules for use by NASA are discussed in the future work section.

These features were preserved from the status quo due to the strong tradition within the ADCO group of using these scheduling processes. Operators have come to expect a predictable weekly pattern. A less predictable solution, in which the days on and days off in the line of work are unique to each scheduling period, would likely cause frustration and confusion (see survey responses in Stakeholder Analysis). Therefore, it was determined that measurable improvements in other areas of the scheduling process would be possible without upsetting these operator expectations. Future iterations of the scheduling process for the ADCO group can and should explore some of the other methods described in the literature.

The scheduling framework, as applied to the ADCO flight controller console shift scheduling problem, can be summarized in the following steps:

1. Requirements analysis
2. Specifications
3. ~~Workforce planning~~
4. Design
    a. ~~Demand modeling~~
    b. Days off scheduling
    c. ~~Shift scheduling~~
    d. Line of work construction
    e. Task assignment
    f. Staff assignment
5. Implementation
6. Test
7. Maintenance

Rationale for the omission of workforce planning, demand modeling, and shift scheduling is given in the sections that follow. Four of Ernst’s steps apply to flight controller console shift scheduling. These steps will be addressed in three steps in the new flight controller console scheduling process. First, the weekly shift rotation and related constraints will address days off scheduling. Second, line of work construction and task assignment will be accomplished together during the optimization step, in which tours of duty are designed. Lastly, the staff assignment step will be performed after the tours of duty are designed.

Workforce Planning

Workforce planning within FOD is currently conducted through a top-down specification of the required number of operators for each certification. Flight controller group leads estimate the total number of weekly person-hours of work required to complete all duties in their group. This number is roughly divided by the 40 hours per week to estimate the number of full-time employees required.

Given that this estimate is not dependent in any way on the efficiency of the console schedule, nor does it take into account work breaks and time off, the problem of workforce planning was not addressed in the application of this study on the ADCO flight controller group. Future work is needed to establish a feedback loop between the schedule design processes described below and workforce planning. This future work could result in workforce reductions if more efficient schedules are able to allow operators to spend a larger share of their work hours on non-console tasks and less hours on console shifts, sleep shifting, and work breaks. The efficiency score described in the design of the Schedule Rotation below could be used in conjunction with other metrics to determine the optimal workforce.

Demand Modeling and Shift Scheduling

Demand modeling for the flight controller scheduling problem consists of a single constraint. There must be one operator assigned to each of the three 8 hour shifts (with a one hour handover) every day. There is no allowance for understaffing or overstaffing.

For flight controller scheduling problems where it is desirable to schedule both the FCR position and the MPSR position in the same process, then the demand model will be non-homogenous. For such a combined FCR/MPSR scheduling case, it may be necessary to implement task constraints in the task assignment module. This applies when certain personnel are certified for the MPSR task but not the FCR task.

For the ADCO flight controller problem addressed in this study, only the homogenous FCR scheduling problem is modeled and solved. Future work is required to solve the mixed FCR/MPSR for groups where operators can serve multiple roles within a planning period.

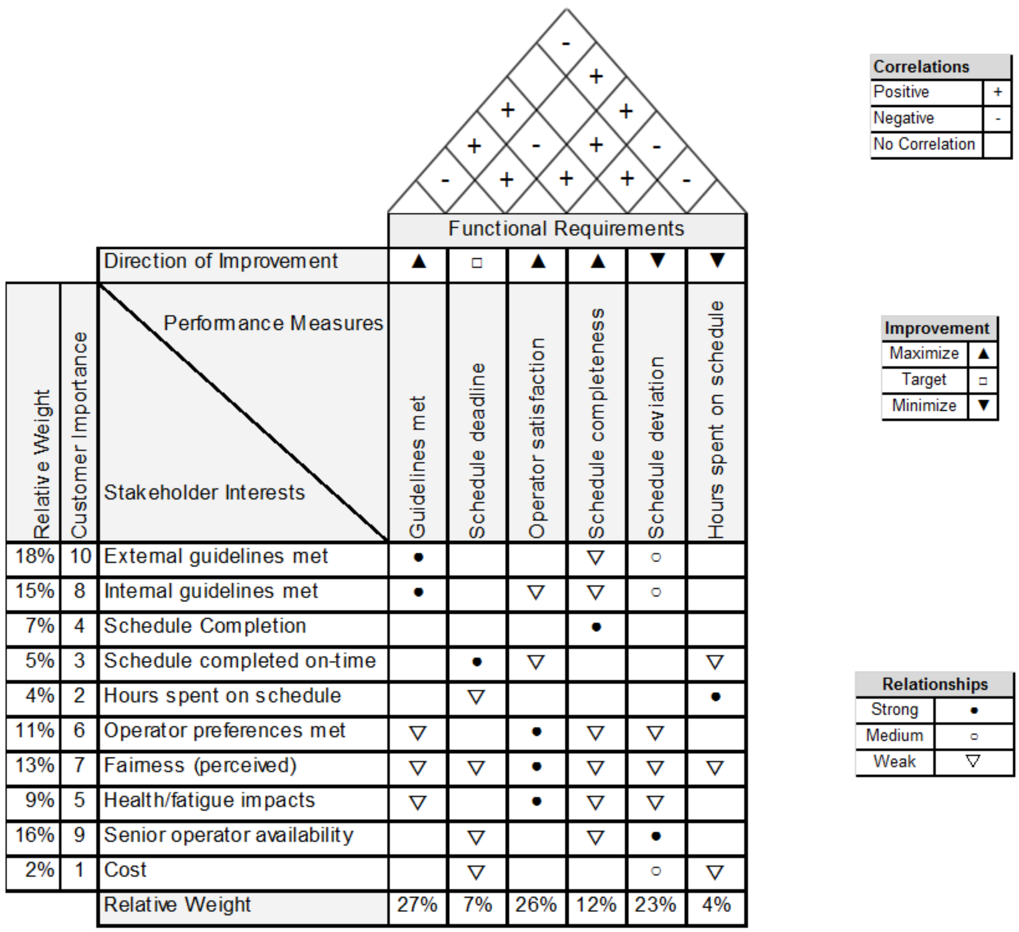
In summary, the flight controller console scheduling problem addressed here uses shift-based demand. Therefore, per Ernst, the shift scheduling step is redundant, as the three shifts per day are known and do not change.

Specifications

Systems engineering recommends that specifications be defined and presented in a relational format. A common representation of specifications, and the stakeholder interests that drive them, is the House of Quality. A house of quality was developed for the flight controller schedule problem and is presented below in Figure 17. The ten stakeholder interests from the stakeholder analysis are shown with six performance measures designed to fulfill those interests. The stakeholder interests are ranked in order of priority based on the data presented in Table 2 from the stakeholder analysis. The six performance measures are listed below with a statement about how they will be measured:

1. Guidelines met (measure number of times guidelines broken)
2. Schedule deadline (set NLT for schedule delivery to calendars)
3. Operator satisfaction (measure operator satisfaction with survey)

4. Schedule completeness (all shifts assigned)
5. Schedule deviation (count number of shifts traded by assignee)
6. Hours spent on schedule (log person-hours required for schedule process)



Relative Weight	Customer Importance	Direction of Improvement / Performance Measures / Stakeholder Interests	Guidelines met	Schedule deadline	Operator satisfaction	Schedule completeness	Schedule deviation	Hours spent on schedule
		Direction of Improvement	▲	□	▲	▲	▼	▼
18%	10	External guidelines met	•			▽	○	
15%	8	Internal guidelines met	•		▽	▽	○	
7%	4	Schedule Completion				•		
5%	3	Schedule completed on-time		•	▽			▽
4%	2	Hours spent on schedule		▽				•
11%	6	Operator preferences met	▽		•	▽	▽	
13%	7	Fairness (perceived)	▽	▽	•	▽	▽	▽
9%	5	Health/fatigue impacts	▽		•	▽	▽	
16%	9	Senior operator availability		▽		▽	•	
2%	1	Cost		▽			○	▽
		Relative Weight	27%	7%	26%	12%	23%	4%

Figure 17 – House of Quality

(Note: The House of Quality was built using FileStage free template [**28**])

The house of quality reveals key relationships between the performance measures that should be considered in the scheduling process design. Of the 10 stakeholder interests identified, the top five holds 73% of the weight. Of the 6 performance measures, 76% of the weight is held by only three: guidelines met, operator satisfaction, and schedule deviation. Design choices should be made to achieve benchmarks selected for these performance measures.

In addition to providing a quantitative measure of the most important requirements and performance measures, the house of quality also provides insight into the relationships between the performance measures. Those performance measures that have a positive correlation will have a synergistic effect. Some performance measures will be negatively correlated, making design improvement more difficult.

For example, the House of Quality shows that two of the top three performance measures (guidelines met and schedule completeness) have negative correlations with a schedule deadline. This implies that allowing some schedule flexibility may be necessary in the implementation phase in order for some of the top stakeholder interests to be met.

These and other insights make the house of quality an important tool for tracking performance in an engineered design process. In addition to defining performance measures and understanding their relationships, measurable benchmarks should be established for each performance measure. Benchmarks for the six selected performance measures above are shown in Table 3.

Table 3:
Performance measures & requirements

#	Performance measure	Requirement
1	Hours spent on schedule (by schedulers)	<15 hrs.
2	Deadline (date of delivery to calendars)	Schedule minus 6 weeks
3	Operator satisfaction (via debrief survey)	>75% satisfaction
4	Schedule completeness	All shifts scheduled
5	Guidelines met	Constraints broken <4 times
6	Schedule deviation	<15% shifts swapped

The select benchmarks are based on data from the previous four years of ADCO console schedules (2015 Quarter 1 through 2018 Quarter 4). Benchmarks were chosen with the intent to either maintain similar performance to the legacy scheduling method or significantly improve on it, depending on the performance measure. Data was not available from the previous two years for all of these performance measures (the concept of tracking benchmark requirements is a new recommendation as of this study). The values for benchmarks 1 through 3 are best guesses based on experience and the stakeholder analysis.

More important than setting ideal benchmarks for first is the process of tracking and using benchmarks at all. Following an initial test and implementation phase, the results will be compared to these requirements and adjusted for future iterations of implementation, if necessary. The benchmark performance should be tracked indefinitely as long as the console scheduling process follows the new design in order for long term performance trending.

Schedule Rotation

Complaints from all internal stakeholders indicated that the current weekly schedule rotation, shown earlier in Figure 5, needed improvement. Prior to Quarter 4 of 2018, the weekly schedule rotation used the 5-operator rotation per Figure 6. The previous rotation had night shifts starting on Thursday night and continuing for seven days. The split of the night shifts into four days and three days, as shown in Figure 5, served to partially resolve some of the stakeholder complaints related to working too many night shifts.

The key complaints that remained after the transition to the new scheduling Quarter 4 of 2018 were related to flexibility, shift load, and impact on other work. As shown in Table 1, one of the top concerns of managers is the availability of senior operators for other tasks. The five- and six-person weekly schedule rotations previously used did not allow for multi-tasking. For example, an operator scheduled to the Day shift, under the previous schedule, must work all five weekdays and therefore cannot support other tasks Monday-Friday that week.

Managers and operators both share a concern related to the impact of rest periods before and after a work block during an assigned week. Managers found that especially before and after Night and Afternoon shifts, they could not assign other tasks to operators without a day off. This is particularly an issue for the Afternoon shifts (J6 and J7 in Figure 5). Operators working J5 (Monday-Thursday) usually take Friday off and cannot be assigned tasks that day. Operators working J6 (Friday-Sunday) usually take at least half of Monday off, and cannot be assigned tasks that day.

Rest periods are also an issue for operators' personal life when working weekends. When working a weekend, there are no formal requirements to schedule personal time off (PTO) before or after the weekend. Rather, operators feel pressure to attend to other tasks on the first business day back from a shift block, even when assigned both Saturday and Sunday console shifts. Therefore, the current weekly shift rotation that assigns three operators to both Saturday and Sunday each week, presents a challenge for work-life balance.

Another flexibility factor that was affecting the efficiency of the scheduling process related to the total number of shift blocks available in the scheduling period, which can be represented by the relationship in Equation 1.

$$S = W*J \qquad \text{(Eq. 1)}$$

$$FR = S/O \qquad \text{(Eq. 2)}$$

$$L = D*N/J \qquad \text{(Eq. 3)}$$

S is the total number of shift blocks in a schedule period

W is the number of sub-periods in a schedule period

J is the number of operators per sub-period in the shift rotation[2]

O is the number of operators available for scheduling

FR (Flexibility Ratio) is the ratio of shift blocks per operator in the schedule period

D is the number of days in the sub-period

N is the number of shifts per day

L is the average length of shift blocks

The legacy ADCO scheduling processing, using the weekly shift rotation in Figure 4, had the following values: W=13, J=6, S=78, O=30, D=7, N=3. This results in a flexibility ratio of 2.6 blocks per operator and an average length of shift blocks of 3.5 days. Low flexibility ratios present difficulties for finding feasible schedule solutions. This is illustrated in the extreme example in Figure 18.

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
N	J1	J1	J1	J1	J1	J1	J1
D	J2	J2	J2	J2	J2	J2	J2
A	J3	J3	J3	J3	J3	J3	J3

Figure 18 – Three-person weekly schedule rotation

If each operator needs to work at least one shift block, then everyone will need to work one 7 days shift block and 9 operators will have to work an extra 7-day shift block. This schedule does not allow for grouping operators into separate buckets with unique

[2] A synonymous definition of J is that it is equal to the number of shift blocks in the sub-period.

levels of staffing. There are two groups: 23 operators who work 7 days and 7 who work 14 days.

As discussed above in the Background and Stakeholder Analysis, flight controller group managers desire an uneven workload across their workforce. With junior operators working more shifts and senior operators working fewer shifts. Some recent data from the ADCO group can serve as an example. In Quarter 4 of 2018, there were 31 ADCO operators to be scheduled with 4 operators in the lowest tier, who were assigned an average of 5.5 shift blocks (4, 4, 4, and 6). With a six-block per week rotation, this left only 2.2 shift blocks each for the remaining 27 operators. An eight-block per week rotation would leave at least 3 shift blocks each. The number of shift blocks expected to be assigned per operator in a schedule drop can have impacts both on the operator's performance as well as the flexibility of the schedule process.

When an operator's shifts are grouped together in only a few number of shift blocks, the cohesion of the operations team is impacted. For example, in Quarter 4 of 2018 as many as 13 operators worked only a single shift block. This single shift block of 2-5 days is that operator's only scheduled time supporting operations in the entire 13-week schedule. They may go many weeks or months until their next shift assignment. A larger value for the length of the shift blocks (L) impacts the ability for the more senior operators to find a suitable shift for assignment. The more senior operators have many other high priority tasks that must be supported. A shift block that takes up an entire week (for example, shift J1 in Figure 6) prevents other tasks from being supported that week. A lower average value for L will allow multi-tasking.

In contrast to the above flexibility concerns, a lower value for L can also have negative impacts on the cohesion of the operations team. Longer shift blocks allow operators to become familiar with recent operational issues and build a rhythm with the other team members assigned to adjacent shift blocks. If the value for L were to be reduced to 1, for example, then all operators would work only a single day each shift block and there would be little operational cohesion.

To balance concerns of flexibility, team cohesion, occupational health, and work-life balance, a measurement scheme was developed in order to evaluate the desirability of any repeating shift rotation. The method consisted of four steps:

1. Develop scoring scheme
2. Generate set of schedule options
3. Score each schedule
4. Select desired schedule

For the scoring scheme, an arithmetic solution was chosen for ease of implementation. For generating random schedules, a script was developed in MATLAB that can generate a specified number of random schedules within a set of design parameters. Each schedule is then scored after generation and the scores are stored in an indexed array for ease of comparison and selection. Decision makers can compare the score of their current schedule to the available randomly generated options to select the weekly schedule rotation that best fits their needs with the highest efficiency score. The specifics of the design of the scoring scheme and example results are discussed further in the sections below.

Line of Work Construction

A complete schedule for an individual operator within the schedule period is referred to as a line of work. This line of work consists of a sequence of days on console and days off console, with the shift supported each day specified. The number of lines of work must be equal to the number of operators available for scheduling.

Solution Style

Several methods were reviewed for schedule development that have been applied to staff scheduling problems in different industry sectors. The bulk of research on staff scheduling problems has focused on development of mathematical models for efficient line of work generation. The list below summarizes some of the methods reviewed. In some cases, these methods are not mutually exclusive and can be combined:

- Operator selection of shift blocks (manual)
- Operator selection of shifts (manual)
- Management assignment of shift blocks (manual)
- Circular schedule with time lag (Rocha, Silva Rocha)
- Cyclic schedules (Laporte)
- Bottom-up days off assignment (Baker)
- Relief teams (Laporte)
- Programming to minimize under or overstaffing (Choi, Eitzen)
- Programming to optimize equity between lines of work (Silva Rocha)
- Programming to optimize stakeholder defined objective function

As previously discussed, what many of these methods have in common is top-down optimization using an objective function within the parameters of input constraints. The exceptions are the methods that use manual assignment of blocks either by the operators themselves or by the decisions makers (management or schedulers). The legacy NASA FOD flight controller scheduling methods use these manual methods. Manual methods are characterized by inefficiencies and a high risk of incomplete schedules, as discussed in the Theory section above. Figure 19 below shows the number of unassigned shifts, or schedule “holes”, found in the last four years of ADCO scheduling data. For these eight scheduling rounds, the average number of holes in the delivered schedule was more than 10 shifts. This illustrates the problem with manual scheduling and why it should be avoided. The stakeholder interests outlined in Table 2 above identify that such a consistent lack of schedule completion will lead to the failure to meet several high priority stakeholder interests.

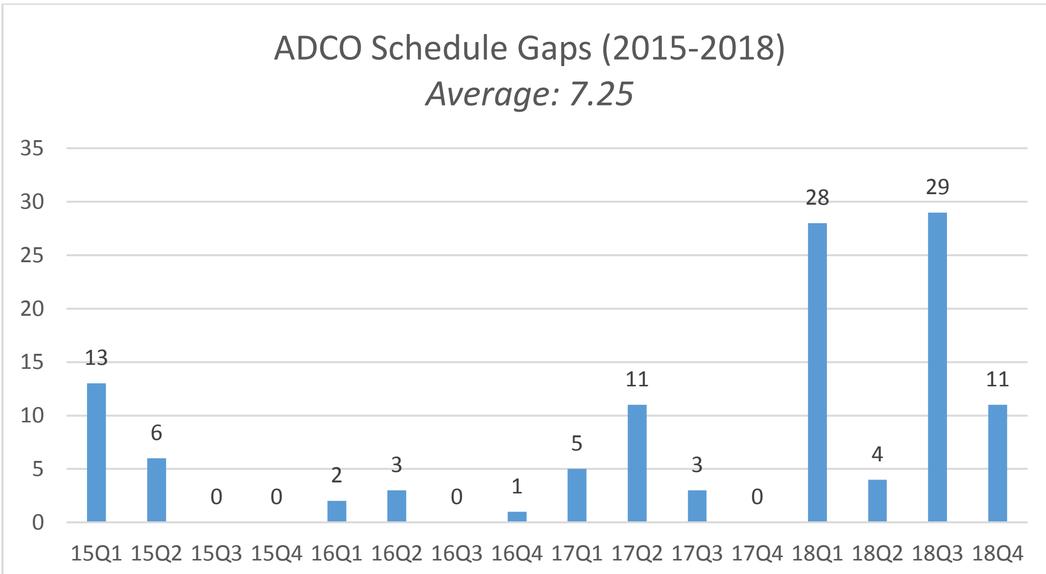


Figure 19 – Historical ADCO schedule gaps

Many of the other options listed above are not applicable to the flight controller scheduling problem. Circular or cyclic schedule design methods will not work for reasons already discussed. Minimizing over/under-staffing is not applicable to the flight controller problem, as staffing must always be exact. Equity between lines of work fits some of the stakeholder interests in Table 2. However, it does not address one of the highest internal stakeholder interests of senior operator availability.

In order to address all of the highest priority stakeholder interests, programming using a unique objective function was selected. The objective function should minimize the overall impact on group efficiency by maximizing the staffing of the least senior operators and minimizing the staffing of the most senior operators. Other interests, such as equity between lines, occupational health impacts, and operator preferences, would be defined as constraints in the model.

Tool Selection

There is a wide array of ILP solutions to choose from for optimization of the flight controller scheduling problem. Many of the methods reviewed provide a general model which can be adapted to most scheduling problems. When selecting a programming method for the ADCO group case study, the main concern was to move from the bottom-up manual method - with the drawbacks described above - to any top-down optimization method which can provide a complete schedule solution. Therefore, method selection was primarily focused on the ease of implementation. The large body of research into these programming methods has continually improved solution time over the many years since Dantzig's first study of the problem. The high efficiency of the more experimental methods were not needed to implement the desired improvements.

Microsoft's built-in Excel Solver can only support approximately 200 decision variables. This limits the scope of possible problem sizes. For a 13 week scheduling period, the largest number of operators that could be accommodated would be 15 in a 15-by-13 matrix of decision variables (one row for each operator and one column for each week in the schedule period). If it is desired to have a column for each shift block per week, this increases the number of columns to ~65 for a 6 person-per-week shift rotation. Thus, the number of operators would be limited to merely 3.

It is evident that the built-in Excel Solver cannot be used for practical versions of the staff scheduling problem. An open source Excel add-in called OpenSolver (www.opensolver.org) [**29**] was evaluated as a replacement for the built-in Excel Solver. OpenSolver was developed as part of COIN-OR. COIN-OR, or Computational Infrastructure for Operations Research, is a project managed by the COIN-OR

Foundation, Inc. to create an open source set of solutions for operational research problems.

The OpenSolver add-in was the winner of the COIN-OR cup award in 2011. The default solver in OpenSolver is the COIN Branch and Cut (CBC) solver. OpenSolver.org describes CBC as "...an open-source mixed-integer program (MIP) solver written in C++." The branch-and-cut method of the CBC solver is in the same class of solution as the branch-and-bound solutions recommended by Eitzen and Silva Rocha. OpenSolver's CBC was therefore selected as the best tool for the ADCO group case study.

Staff Assignment

Staff assignment was the step in most need of improvement in the ADCO group. The current method involved a free-for-all, or "open season," method in which the first operators to access the schedule spreadsheet were allowed to self-schedule their most desired shift blocks. This method has many drawbacks. The self-assignment of individual shift blocks (either all at once or in scheduling rounds) is a bottom-up method which contributed to the many shift holes during each schedule period, as illustrated in Figure 19. Additionally, this method is widely considered unfair due to the randomness of timing: whoever is the first operator to see the spreadsheet when it is released gets the best choice. Operators who are on leave or otherwise busy generally get the last and worst pick of the shift blocks.

There is a sparsity of research concerning different options for conducting the staff assignment step. A brainstorming exercise identified the options in Table 4. The options are sub-divided into three parameters: what is assigned, method of assignment, and decision parameter. The options shown result in 24 possible combinations. The decision parameter options are defined below.

Table 4:
Staff Assignment Options

Assignment	**What is assigned**	**Decision parameter**
Self-assign	Days	Priority
Manager-assign	Shift blocks	Teams
auto-assign	Lines of work	Preference
		First-come first-serve

First-come first-serve is the current method in ADCO and is described above. Team assignment sub-divides the workforce into groups referred to as “teams” who always work together. “Work together” can be defined in different ways. A team could be three people (one for each shift of the day) or a team could be the number of people required to fill the weekly schedule rotation. Team based assignment would require implementation of constraints in the design of the weekly schedule rotation and line of work design steps in the scheduling process. These constraints would be necessary to ensure that the teams are always together on their assigned days or weeks.

Preference-based assignment would involve each operator providing preferences for which shifts or lines of work they would like to be assigned. Then a decision maker (depending on if it is self, manager, or auto-assignment) would assign shifts based on preferences. By contrast, priority-based assignment would perform the staff assignment based on a pre-designated priority list. Priority could be based on seniority, operator certification level, or some other desired parameter.

For the ADCO group case study, self-assignment of lines of work based on preferences was chosen for the staff assignment step. This option provides operator input and choice to improve fairness and equity while employing the efficiency and top-down advantages of line of work scheduling. See the Design section for the specific description of the process design. See the Results section for a review of how the process was applied to the ADCO case study.

Design

In order to apply the theoretical framework to a schedule period using the above methods, the scheduler must answer several key questions which will impact the schedule's design. As defined in Equations 1-3 above, values for N, D, O, and W are given by the scheduler in order to select the shift rotation and design lines of work.

D is the number of days in the sub-period

N is the number of shifts per day

O is the number of operators available for scheduling

*W is the number of sub-periods in a schedule period (W*D is the length of the schedule)*

Schedule Rotation

The new method for designing the weekly shift rotation consisted of four steps:

1. Develop scoring scheme
2. Generate set of schedule options
3. Score each schedule
4. Select desired schedule

Scoring Scheme

The approach to scoring options for the weekly shift rotation was to account for concerns of flexibility, efficiency impacts, operator work-life balance impacts, and operator health impacts. An arithmetic scoring scheme was developed which quantitatively accounts for most of these concerns. However, a drawback in the scheme, due to the efficiency impacts of switching out operators, high scores were consistently awarded to schedules in which the night and afternoon shifts are worked by only one person for the whole week. These schedules do not achieve the desired operator work-life balance and health effects recommended by the literature review and stakeholder analysis. A workaround for this limitation was accounted for as part of step 4 and is discussed below.

The scoring scheme is defined in Equations 4-7.

$$\text{Score} = PR*FQ \qquad \text{(Eq. 4)}$$

$$PR = (MP-Cost)/MP \qquad \text{(Eq. 5)}$$

$$MP = ((O-N)*5/7+N)*D \qquad \text{(Eq. 6)}$$

$$FQ = 1-1/(10*FR) \qquad \text{(Eq. 7)}$$

PR = Productivity Ratio

FQ = Flexibility Quotient

Cost = combined bleed cost and switching cost of shift rotation

MP = Maximum Productivity

The Productivity Ratio (PR) is a measure of the total productivity achieved by the workforce and is represented as a ratio between the productivity achieved in a given schedule and the maximum possible productivity, measured in person-days.

The Maximum Productivity (MP) is equivalent to the total person-days of work that could be achieved if there were no switching cost or bleed costs. This is equivalent to all but three of the operators working 5 days a week on non-console tasks and the remaining three working 7 days a week on console.

The flexibility quotient is a function with values between 0.9 and 1.0 based on the flexibility ratio.

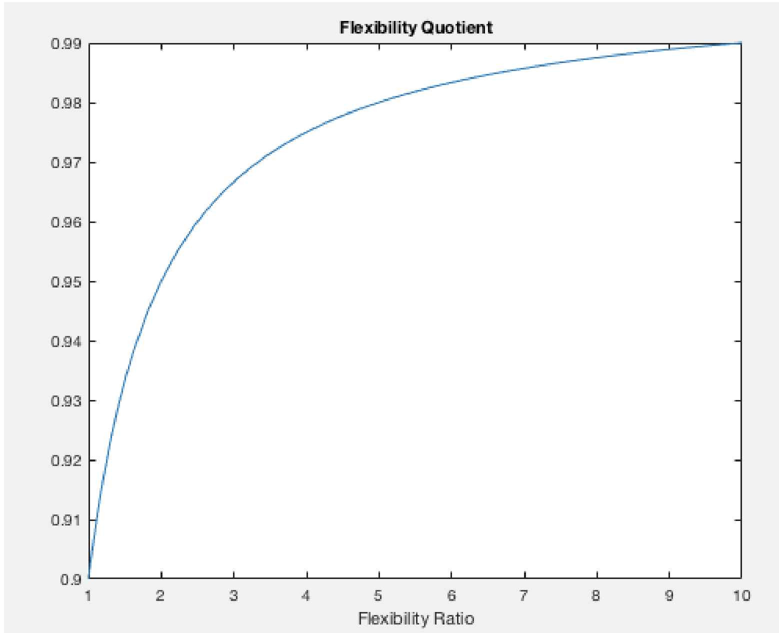


Figure 20 – Flexibility Quotient (FQ) plotted on interval [1 10]

This flexibility ratio represents the number of available shift blocks per operator in the schedule period. A low flexibility ratio indicates less options for assignment per person, which indicates less flexibility in the different kinds and numbers of shifts that can be assigned across the workforce. In an extreme example, the weekly schedule rotation shown below in Figure 20 has a flexibility ratio of only 1.3 for a workforce of 30 operators.

The productivity of a weekly shift rotation is the difference between the maximum productivity and the efficiency cost of the weekly shift rotation. This cost is the sum of the switching cost and the bleed cost.

Switching cost is the cost of lost efficiency due to switching operators throughout the week. This cost is based on the theory that the more consecutive shifts a given operator staffs, the more familiar they will be with current operations, making them more effective at their tasks and less prone to error.

Bleed cost is the cost of lost efficiency in other non-console tasks due to being on console. This cost is only due to working nights, afternoons and weekends. A summary of the various costs that can add up to the total cost of a given weekly shift rotation is given in Table 5.

Table 5:
Summary of cost factors

Type of Cost	Value
Switch cost	0.5 per person in schedule
Bleed cost	1.0 per person on afternoonss
Bleed cost	2.0 per person on nights
Bleed cost	1.0 per person working Sat/Sun pair

Schedule Options

A large number of possible weekly shift rotations needed to be evaluated to identify the ideal choice for a given workforce size and schedule period length. Figure 21 provides the lower bound and Figure 22 provides the upper bound on the possible values for cost and number of operators in the weekly shift rotation. The cost for the schedule in Figure 21 is 4.5 with 3 operators. The cost for the schedule in Figure 22 is 31.5 with 21 operators.

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
N	J1	J1	J1	J1	J1	J1	J1
D	J2	J2	J2	J2	J2	J2	J2
A	J3	J3	J3	J3	J3	J3	J3

Figure 21 – Three-person weekly rotation

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
N	J1	J2	J3	J4	J5	J6	J7
D	J8	J9	J10	J11	J12	J13	J14
A	J15	J16	J17	J18	J19	J20	J21

Figure 22 – 21-person weekly rotation

Using the following inputs (W=13, O=30, D=7, N=3), the scores for these schedules were calculated and compared to the scores for the five flight control groups surveyed (group D excluded, as they do not use a weekly rotation). The results are shown in Table 6. Note that the Maximum Productivity (MP) for these inputs is 156. Note also that Group C cost was approximated due to their weekly day shifts being variable.

Table 6:
Comparison of weekly schedule rotation scores

	FQ	**Cost**	**PR**	**Score**
Figure 21	92.3%	4.5	97.1%	89.6%
Figure 22	98.9%	31.5	79.8%	78.9%
Group A legacy	96.7%	12.5	92.0%	89.0%
Group B legacy	95.4%	9.5	94.0%	89.6%
Group C legacy	95.4%	8.5*	94.6%	90.2%
Group E legacy	96.2%	12	92.3%	88.8%
Group F legacy	95.4%	9.5	94.0%	89.6%
Best (Figure 23)	96.7%	7.5	95.2%	92.0%

For comparison, the highest score identified for these inputs - using a random schedule creation script in MATLAB (see Appendix E) - is also shown. This best schedule corresponds to the rotation shown in Figure 23 below.

	Sun	Mon	Tue	Wed	Thu	Fri	Sat
N	J1	J1	J1	J1	J1	J1	J1
D	J2	J3	J3	J3	J4	J4	J5
A	J6	J6	J6	J6	J7	J7	J7

Figure 23 – Best weekly rotation example

Note that this "best" schedule suffers from some weaknesses that are not accounted for in the scoring scheme. First, the high score of this schedule is in part due to the low cost due to only one operator working all of the night shifts. As previously discussed in the Literature Review and Theory section, long stints of night shifts are not recommended. Second, the same operator working night shifts may not be working two weekend days in a row, but they are working two weekend days in their shift block in back-to-back weekends. If a "weekend off" constraint were to be imposed, this schedule would be infeasible, and a schedule that splits the night shifts across two operators would need to be selected

These weaknesses of the "best" schedule in Figure 23 highlight the need to consider other constraints and factors when selecting the schedule rotation. The score from Equation 4 should not be used alone to select the rotation. Rather, the schedule with the best score while meeting all other constraints should be selected.

Line of Work Construction

The second step in generating a complete schedule is to assemble the shift blocks defined by the weekly schedule rotation into lines of work that can be assigned to the workforce in the staff scheduling step. In certain forms of staff scheduling, such as manual assignment of shift blocks, the line of work construction step is combined with the staff assignment step. For the ADCO case study, the staff assignment step will involve selection of lines of work, which requires them to be constructed ahead of time. The lines of work will be anonymous - meaning they are generated with no specific personal preferences or considerations for the leave and work calendars of the workforce. These constraints will be handled in the staff assignment phase.

Line of work generation using an ILP solver requires the design of three distinct modules of the problem: the decision variable matrix, the constraints, and the objective function.

The decision variable matrix is the matrix of values that will be adjusted by the solver to complete the schedule and meet the constraints. A successful schedule will arrange the decision variables in such a way that one flight controller is assigned to each shift every day of the schedule period.

The constraints will ensure that guidelines are implemented in the solution. An example would be the guideline of no more than 10 consecutive days assigned to a shift. A constraint must be included in the solver that restricts the sum of shift coverage over 10 days to not exceed 9.

The objective function will give the solver an objective parameter to optimize while evaluating solutions. The objective function can be designed to optimize any aspect of the problem, and must be designed in order to meet the constraints or requirements specified for the schedule.

Decision Variable Matrix

Several options were explored for the design of the decision variable matrix. Figure 24 shows three options that were compared for the decision variable matrix. The schedule rotation modeled is the legacy ADCO 7-block schedule from Figure 5.

	D1	D2	D3	D4	D5	D6	D7
Oper 1	1	1	1	1	0	0	0
Oper 2	0	0	0	0	1	1	1
Oper 3	2	2	0	0	0	0	0
Oper 4	0	0	2	2	2	0	0
Oper 5	0	0	0	0	0	2	2
Oper 6	3	3	3	3	0	0	0
Oper 7	0	0	0	0	3	3	3

	D1	D2	D3	D4	D5	D6	D7
Oper 1 N	1	1	1	1	0	0	0
Oper 1 D	0	0	0	0	0	0	0
Oper 1 A	0	0	0	0	0	0	0
Oper 2 N	0	0	0	0	1	1	1
Oper 2 D	0	0	0	0	0	0	0
Oper 2 A	0	0	0	0	0	0	0
Oper 3 N	0	0	0	0	0	0	0
Oper 3 D	1	1	0	0	0	0	0
Oper 3 A	0	0	0	0	0	0	0
Oper 4 N	0	0	0	0	0	0	0
Oper 4 D	0	0	1	1	1	0	0
Oper 4 A	0	0	0	0	0	0	0
Oper 5 N	0	0	0	0	0	0	0
Oper 5 D	0	0	0	0	0	1	1
Oper 5 A	0	0	0	0	0	0	0
Oper 6 N	0	0	0	0	0	0	0
Oper 6 D	0	0	0	0	0	0	0
Oper 6 A	1	1	1	1	0	0	0
Oper 7 N	0	0	0	0	0	0	0
Oper 7 D	0	0	0	0	0	0	0
Oper 7 A	0	0	0	0	1	1	1

	B1	B2	B3	B4	B5	B6	B7
Oper 1	1	0	0	0	0	0	0
Oper 2	0	1	0	0	0	0	0
Oper 3	0	0	1	0	0	0	0
Oper 4	0	0	0	1	0	0	0
Oper 5	0	0	0	0	1	0	0
Oper 6	0	0	0	0	0	1	0
Oper 7	0	0	0	0	0	0	1

Figure 24 – Decision variable matrix options

In the first option, each variable is an integer value between 0 and 3 that corresponds to whether a given operator is working no shift, Night shift, Day shift, or Afternoon shift on a given day. Constraints would need to be constructed that ensure one variable in each column takes a value of 1, 2, or 3. To ensure the schedule is constructed according to the weekly schedule rotation blocks, constraints would need to be constructed ensuring that if an operator is assigned one shift, they are assigned the other corresponding shifts in that block.

In the second option, each variable is a binary value. There are three rows per operator corresponding to whether the operator works Night, Day, or Afternoon shift on a given day. Constraints would need to be constructed to ensure that the sum of the values in each column equals 3 for complete coverage. Additional constraints would need to be constructed to prevent each operator from being assigned more than one shift each day. Lastly, constraints would need to be constructed to enforce the shift block design.

In the third option, each variable is a binary value corresponding to whether a given operator is working one of the available shift blocks in the given week. This option reduces the number of additional constraints that need to be constructed in the model. None of the additional constraints reference above for the examples in the first two options would be required. However, this option is restrictive in terms of the flexibility of shift selection. Using this design, all shifts must be assigned via the specified shift blocks and little deviation is possible without redefining a given shift block. As will be discussed below in the design of the staff assignment process, the need for flexibility and manually constructing some lines of work while the solver designs the remaining lines of work can be advantageous in some scenarios.

For the ADCO case study, the third option was selected for the design of the decision variable matrix. The first option was rejected due the non-binary decision variables, which would require conditional constraints. The second option as rejected due to a tendency for the solver to find the problem over-constrained in preliminary tests. The definition of this decision variable matrix is shown by the O-by-S matrix X in Equation 8.

$$X = \begin{bmatrix} x_{1,1} & \cdots & x_{1,S} \\ \vdots & \ddots & \vdots \\ x_{O,1} & \cdots & x_{O,S} \end{bmatrix} \quad x_{i,j} \in (0,1) \qquad \text{(Eq. 8)}$$

Constraints

The number of constraints that can be built into the model is restricted at the low end by guidelines and restricted on the upper end by the ability for the solver to compute a solution. As the value of O (total operators who must be scheduled) is increased, the flexibility of the schedule increases and more restrictive constraints can be accommodated. For example, a constraint that requires three weeks off between night shifts can be accommodated with a large value for O in a 13-week scheduling period. For a small team of 7 operators, a schedule cannot be constructed with 3 weeks between night shift blocks without violating other constraints. Therefore, imposing a constraint of three weeks between assignment of Block 1 or Block 2 in the third example in Figure 24 would not produce a feasible solution (assuming blocks 1 and 2 are the night shifts).

The model for flight controller scheduling in the ADCO case study was designed using four base constraints, shown in Equations 9-12.

$$\sum_{i=1}^{O} x_{i,j} = 1 \quad \text{for j =1,...,S} \qquad \text{(Eq. 9)}$$

$$\sum_{j=1}^{J} x_{i,(J*w+j)} \leq 1 \quad \text{for i = 1,..,O; for w = 0,...,W-1} \qquad \text{(Eq. 10)}$$

$$\sum_{j=1}^{J} x_{i,(J*w+j)} + \sum_{j=1}^{J} x_{i,(J*(w+1)+j)} \leq 1 \quad \text{for i=0,...,O; for w = 0,...,W-1} \qquad \text{(Eq. 11)}$$

$$\sum_{j=1}^{S} x_{i,j} \geq 1 \quad \text{for i=1,…,O} \qquad \text{(Eq. 12)}$$

Equation 9 models the completion constraint, which ensures that each shift is assigned to one, and only one, operator.

Equation 10 models the shift assignment constraints, which ensures that each operator is assigned to only one shift block per week.

Equation 11 models the week off constraint, which ensures that an operator has at least one week between assigned shift blocks in the schedule period.

Equation 12 models the proficiency constraint, which ensures that each operator is assigned at least one console shift in the schedule period.

Note that the shift assignment constraint and the week off constraint are more restrictive than would be necessary to meet all guidelines defined by most stakeholders. Referring back to Figure 5, an operator could work a J1 and J5 shift block in the same week, or a J6 and a J7 block in back to back weeks. These example scenarios have sufficient breaks between shifts and do not violate any shift work best practices (they rotate forward and provide days off before changing shifts). Future iterations of the model can include more complex constraints that account for these various shift block combinations between and across weeks. For the ADCO case study use of the model, the simpler constraints shown above were chosen in order to reduce the number of constraints required. It was found that with O>>J, as in the case of the ADCO group, feasible solutions are easily found with the shift assignment and week off constraints.

Using the decision variable matrix modeled in Equation 8 and the base constraints in Equations 9-12, OpenSolver was found to generate a feasible solution for a schedule problem of W weeks, with O operators, and J shift blocks per week. A heuristic approach was used to assess any modifications to the resulting solutions. Additional constraints were added to achieve the desired equity and fairness between operators, or to provide sufficient spacing between night shift blocks.

Discussion of some of the more critical additional constraints that were implemented in the ADCO case study for 2019 Quarter 1 and 2019 Quarter 2 will be included in the results section below. However, due to the trial-and-error heuristic approach and the ease of implementing additional constraints in the Excel model with OpenSolver, an exhaustive list of all constraints tested or used will not be included.

Objective Function

Per the specifications outlined in Table 3, the objective function was chosen as the mechanism for ensuring the need for senior operator availability is achieved. Senior operator availability was found to be of high interest to both internal and external stakeholders per the stakeholder interests in Table 2. The objective function is described by Equation 16, using inputs from the matrices defined in Equations 13-15.

$$Y = \begin{bmatrix} y_{1,1} & \cdots & y_{1,F} \\ \vdots & \ddots & \vdots \\ y_{O,1} & \cdots & y_{O,F} \end{bmatrix} \quad y_{i,f} \in (0,1) \qquad \text{(Eq. 13)}$$

$$M = \begin{bmatrix} m_{1,1} & \cdots & m_{1,J} \\ \vdots & \ddots & \vdots \\ m_{N,1} & \cdots & m_{N,J} \end{bmatrix} \quad m_{n,j} \in (0,\ldots,D) \qquad \text{(Eq. 14)}$$

$$C = \begin{bmatrix} c_{1,1} & \cdots & c_{1,F} \\ \vdots & \ddots & \vdots \\ c_{N,1} & \cdots & c_{N,F} \end{bmatrix} \quad 0 <= c_{n,f} <= 1 \qquad \text{(Eq. 15)}$$

$$\sum_{i=1}^{O} \sum_{w=0}^{W-1} \sum_{j=1}^{J} \sum_{f=1}^{F} \sum_{n=1}^{N} x_{i.(J*w+j)} y_{i,f} m_{n,j} c_{n,f} \qquad \text{(Eq. 16)}$$

F is the number of buckets in the workforce

Y defines which bucket each operator is in

B defines the size of each shift block in days

M defines the shift for each shift block

C defines the cost for each combination of bucket and shift

Each bucket, or type of operator, is assigned a cost value for working each of the shifts (Night, Day, and Afternoon, in this case). These costs are heuristically determined based on the impact of that operator being on console instead of contributing to the group's productivity in other tasks. For example, the flight controllers who are also certified instructors and must run the training simulations are given a very high cost to

Afternoon and Night shifts, as they cannot support a simulation on the day of their shift nor the day after. By contrast, the junior flight controllers in the lowest bucket are given the lowest cost for working Nights due to having fewer high priority off-console tasks.

Note that this cost function is separate from the cost function used to score the weekly schedule rotation, which accounts for the generic bleed-over cost of having operators on console instead of in the office. The objective function defined in Equation 16 is specific to the type of operator assigned to each shift block.

Note that they Y, M, and C matrices must be defined by the group decision makers. The M matrix (and the value of F) are dependent upon the weekly schedule rotation chosen in the previous design step. The Y matrix is dependent upon the current makeup of the workforce. The C matrix is defined by the group decision makers, as described above.

Minimization of this objective function will tend to assign more shifts to the lower cost buckets and fewer shifts to the higher cost buckets (expected to correspond to more junior and more senior flight controllers, respectively) while also assigning the least impactful shifts to each type of operator. This is expected to mean more Day shifts for the senior operators and more Night and Afternoon shifts for junior operators - although it will depend on the values of C selected.

Staff Assignment

From the options discussed in the Methods section, self-assignment of lines of work based on preferences was selected for the staff assignment step. This assignment method was designed as a 5-step process:

1. Review lines of work
2. Preferences
3. Conflict resolution

4. Line of work assignment
5. On-call shift assignment

Review Phase

The review phase allows all team members to see the planned schedule with the line of work options before scheduling begins. Review phase is intended to allow feedback from the workforce on the design of the lines of work. They can identify any issues with the schedule, such as night shifts spaced too close together, or other concerns, and the lines of work can be redesigned and reposted.

Preference Phase

During the preference phase, each operator identifies their top choices for line of work assignment for themselves. These preferences are recorded publicly where all operators can see their colleagues' choices. The number of preferences that should be recorded will depend on the size of the workforce and whether they are divided into buckets. Generally recording the top three preferences should be sufficient to resolve all conflicts. An example set of preferences are provided below for a subset of a workforce. This is intended to represent a bucket of 6 operators who are part of a larger flight controller workforce.

Table 7:
Preference Table Example

Name	**Preference 1**	**Preference 2**	**Preference 3**
Oper A	1	5	3
Oper B	1	2	3
Oper C	4	5	1
Oper D	3	2	6
Oper E	3	6	2
Oper F	1	5	4

In this example, lines of work 1 and 3 were very desirable and were selected by most of the 6 operators as their first preference. Only one operator can be assigned each line of work. The conflicts are resolved in the next phase.

Conflict Resolution Phase

After all operators have recorded their top three preferences, the conflict resolution phase begins. In this phase all operators review the preference table for overlapping preferences with other operators. In this case, Operator A, B and F need to resolve the conflict with line of work number 1. Operators D and E need to resolve the conflict with line of work number 3.

Conflict resolution phase should begin with the operators discussing their conflict to find an easy solution. In some cases one person's preference may be stronger than another. For example, Operator F may be just as happy with line of work number 5 as line of work number 1. In other cases the resolution may not be clear and a compromise may be needed. One choice for the A, B, F conflict is to allow either Operator A or F to have line of work 1, so that they do not have a conflict with their second preference. This would allow Operator B to work their second preference of line of work 2 and the third person can work line of work 5. If Operator B is given line of work 1, then Operator A or F may end up having to settle for their third preference.

If the operators cannot resolve their conflict on their own, then the issue will be raised to the schedule team and management, who will work out a compromise or determine a way to break the tie, such as giving the first choice to the most senior operator.

Line of Work Assignment Phase

In the line of work assignment phase, the final preferences based on the conflict resolution decisions are used to match individual operators to lines of work. The names are matched to the lines of work on the schedule spreadsheet and recorded as official via whatever rostering tool is used by the organization (in the case of the flight controller's in the Mission Control System, the Britannica's Fox Training Management System is used to assign the work shifts to each operator's Microsoft Outlook calendar).

On-call Shift Assignment Phase

The final step in staff assignment is to assign one person to be on-call for each day in the schedule period.

Schedulers have a similar set of choices for the on-call scheduling sub-step as they do for the overall staff scheduling step. The options in Table 4 can be applied to on-call scheduling. In the current ADCO scheduling process, prior to this study, on-call shifts were assigned in first-come first-serve self-assigned shift blocks. Applying this method to on-call scheduling results in the same concerns and limitations as the previously utilized bottom-up process for staff assignment.

For the updated framework, a process of self-assigned on-call blocks assigned via a preference scheme was chosen. In order to prevent a scheduling dilemma due to bottom-up block assignment, the schedule is split into a number of blocks equal to a multiple of the number of operators who will be assigned on-call. This ensures that all on-call blocks will be assigned through the preference and conflict resolution phases. Note that in the ADCO flight controller group, bucket 1 operators cannot be assigned on-call. Therefore, sufficient on-call operators must be selected from the remaining three buckets.

The on-call assignment process used for ADCO in Quarter 2 of 2019 is described here as an example. A 12-week scheduling period was described as 24 on-call blocks - twelve Monday-Friday blocks and twelve Saturday-Sunday blocks. Management assigned twelve operators to be responsible for Monday-Friday on-calls and twelve operators to be responsible for weekend on-calls. Each set of twelve operators then ranked their preferences for the available on-call blocks. Following a conflict resolution phase, one of each of the 24 on-call blocks was assigned to each of the operators, completing the on-call scheduling with no gaps.

Alternative Staff Assignment Options

In practice, the flight controller workforce does not always divide nicely or evenly into three or four buckets with at least several operators in them. It was found in both the 2019 Quarter 1 and 2019 Quarter 2 case studies that some buckets were too small to apply this 5 step framework for staff assignment. An alternative option was needed for small buckets.

Small bucket sizes (2-4 people) provides some advantages that allow certain staff assignment options that are not available with larger buckets. Preference based assignment for large buckets must provide a limited set of options in order to guarantee a complete schedule. This is the reason that preference based assignment of lines of work was chosen for the group as a whole. However, for a small bucket, each operator can construct their own line of work and compare it to their colleagues chosen line of work for conflicts. Conflict resolution in this case is simpler given the limited number of people involved in the negotiations.

This process could be described as self-assigned shift blocks using first-come first-serve. When the small bucket of people utilizing this process are allowed to select from all days in the schedule (meaning no other operators have been scheduled for any shifts yet), the operators are able to come to a compromise and assign their desired shifts. This alternative option for small buckets can quickly accomplish all of Ernst’s steps for staff assignment using a self-assigned manual process.

Following the staff assignment for the small buckets at the start of the process, the process then proceeds to line of work construction for the remaining operators in the larger buckets who must be scheduled, with the shift blocks assigned to the operators in the small bucket hard-coded as assigned shifts rather than set as open variables in the model. This alternative method was used effectively for one small bucket in the 2019 Quarter 1 case study and for two small buckets in the 2019 Quarter 2 case study. Specific results are discussed in the sections below.

This alternative option was implemented as a step 0 “review phase,” which occurs prior to the review phase in the five step staff assignment process presented above. Use of this pre-selection step 0 should be used on a limited basis, as there is a risk of alienating the workforce segment that does not participate in pre-selection. A post-scheduling survey should be used to gauge the perceived fairness of the overall staff scheduling process and make adjustments to pre-selection and other steps if necessary to balance employee satisfaction.

Implementation, Testing, and Maintenance

A plan for implementation, testing, and maintenance is necessary to ensure effective use of the new process. A plan for implementation and testing will ensure stakeholders are receptive and that their feedback is used to iterate and improve the process and related tools. A plan for maintenance is needed to ensure that any future changes to requirements, tools, or other process inputs will trigger a process design iteration in order that the process stays relevant and effective.

The plan for implementation involves clear communication to all internal stakeholders. Instructions for implementing the new process must be documented and made available. A timeline for completing the process, especially the steps in the staff assignment process, should be established and clearly communicated. The plan for rollout of the process to the flight control group will follow the below steps:

1. Document instructions and schedule
2. Brief group decision makers
3. Present process at group meeting
4. Implement staff assignment process
5. Debrief process at group meeting
6. Collect feedback via anonymous survey

Note that the collection of feedback is critical. The survey is needed to verify that the process has met the benchmarks for operator satisfaction. Additionally, the survey is necessary to collect various feedback that should be utilized to update the design process.

The plan for testing and maintenance is to collect all metric and survey data and compare it to the established benchmarks. Metrics that do not meet the benchmarks should be analyzed and possible design changes proposed to meet the benchmark on the next schedule iteration. Changes to the process should be tried on subsequent schedule periods.

The survey design is provided below. Determination of operator satisfaction will be the aggregate percentage of questions 2, 4, 5, 6, 7, 9, and 10 in which operators respond positively, negatively, or neutrally. "Satisfied" will pertain only to positive responses. Free text feedback in question 10 will be assessed as either positive, negative, or neutral in nature. Note: the questions below represent a generic version of the survey design. The exact survey design used in the case study for ADCO Quarter 1 2019 scheduling is provided in Appendix C.

1. *What bucket were you in for [X] quarter scheduling?*

2. *How would you rate the efficiency of the scheduling process used for [X] quarter scheduling?*
    a. *More time than previous methods*
    b. *Same amount of time as previous methods*
    c. *Less time than previous methods*
3. *How many hours did you spend on [X] quarter scheduling?*
4. *How would you rate the flexibility of the [X] quarter scheduling process?*
    a. *More flexible than previous methods*
    b. *Same flexibility as previous methods*
    c. *Less flexibility than previous methods*
5. *How would you rate the fairness of the [X] quarter scheduling process?*
    a. *More fair than previous methods*
    b. *Same fairness as previous methods*
    c. *Less fair than previous methods*
6. *How would you rate the fairness of the night shift schedule you were assigned?*
    a. *I was not assigned night shifts*
    b. *Night shift schedule was fair*
    c. *Night shift schedule was not fair*
7. *If you could choose the scheduling method for future quarters, which would you choose?*
    a. *Legacy method*
    b. *New method*
    c. *Other*
8. *Please rank the criteria below based on their importance to you for scheduling method.*

a. Schedule completeness

b. Schedule fairness

c. Schedule flexibility

d. Management guidelines meth

e. Night shift assignments are fair

9. *How do you feel about the number of shifts you were assigned for [X] quarter?*

   a. Too few

   b. About right

   c. Too many

10. *Please provide any additional comments or feedback you have on the scheduling process.*

Survey results should also be used to incorporate operator feedback regarding other aspects of the process design, including constraints and guidelines. The free text comments provided in question 10 should be shared with all internal decision makers. These anonymous comments will provide valuable insight into how the scheduling process is affecting operator's work-life balance.

Instructions for how to complete a schedule process - from selection of inputs (guidelines, schedule period duration, weekly rotation), to have to conduct staff scheduling, to post-scheduling data collection - should be written and available in a known location. These instructions may be needed in case of turnover on the scheduling team.

Summary of Process Design

The design process for the proposed framework requires first data from a stakeholder analysis to define performance measures and requirements (together referred to as specifications). Once these inputs are available, the below outline can be followed in order to design a schedule creation process that can be used repeatedly for a staff scheduling problem of any size or duration.

- Define schedule parameters
- Design weekly shift rotation
    - Develop scoring scheme
    - Generate set of schedule options
    - Score each schedule
    - Select desired schedule
- Design line of work construction process (tour scheduling)
    - Select variable matrix
    - Define constraints
    - Define objective function
- Design staff assignment phase
    - Pre-selection
    - Review phase
    - Preference phase
    - Conflict resolution
    - Scheduling phase
    - On-call scheduling
- Define implementation steps
    - Deadlines for implementation
    - Stakeholder buyoff of process
    - Schedule development
    - Staff assignment
    - Debrief/survey

- Design iteration

In order to apply this design process to the case study of the flight controller scheduling problem - and specifically, the ADCO group schedule - specific design choices have been described for each of the steps in this outline. The scoring scheme, matrices, constraints, and objective functions described above were applied to a case study in the ADCO group to demonstrate the process. Changes to the design as the process was iterated through multiple schedule periods are described below in the results section.

Data Analysis

The methods described above will be used to compare theoretical results to the actual schedule generated in previous ADCO flight controller schedule periods. To assess whether the new methods would result in measurable improvement to performance measures or other metrics, the following data analysis techniques shall be employed.

Data from previous ADCO schedules will be collected and tested for normality using a Shapiro-Wilk test using IBM's SPSS software package. A significant p-value of 0.05 shall be used to indicate normality. Theoretical results will then be generated using the design described above also compiled and tested for normality using the same significance value. Lastly, a t-test will be used to determine if the population of theoretical scores represents a statistical improvement. Again, a significance value of 0.05 shall be used.

For experimental data from practical implementation ($n = 2$), the results will be considered significant if they fall outside 2σ of the mean for the historical schedules.

CHAPTER IV:

IMPLEMENTATION

Results

Description of Case Studies

The methods described above were applied in two separate case studies to the ADCO flight controller console scheduling problem: a solution comparison on historical data and a practical implementation of the process for the 2019 console schedule.

For the solution comparison, data was collected on the ADCO console scheduling process from 2015 to 2018, which included 16 separate scheduling periods in which the legacy staff scheduling process was applied. The shift rotation scoring scheme and schedule objective function described above were applied to the legacy schedules to obtain baselines. The suggested line of work construction process was then applied, using OpenSolver and the constraints given above, to obtain a theoretical improved schedule. Resultant scores were then compared.

For the practical implementation, the entire framework described above in Summary of Process Design was used to create the ADCO console schedule for two consecutive schedule periods: 2019 Quarter 1 and 2019 Quarter 2. Data was collected on several metrics, including the performance measures given in Table 3. Operator satisfaction was measured through a survey conducted after the staff scheduling step was completed. The metrics were then compared to the same measures from the legacy ADCO scheduling method from 2015 to 2018. However, for three of the six performance measures, no data was available in the historical data for comparison. Therefore, the rotation scores and schedule scores are used as additional metrics for comparison, although they are not specifically defined as performance measures.

Note that initially, data was only collected for 2016 to 2018 for time management reasons. When it was found that a W/S test for normality failed on an important metric (number of swaps), data from 2015 was also compiled to increase n from 12 to 16 and a more advanced Shapiro-Wilk normality test was used on the final dataset.

Solution Comparison

The historical data for the ADCO flight controller schedule from 2015 to 2018 was available in three forms. First, the staff scheduling spreadsheets were available from the group schedulers. Each spreadsheet showed the planned staff schedule for the given schedule (usually a 13-week, 91-day, quarter). From this spreadsheet, it was possible to determine the equivalent X matrix schedule for each quarter. Second, the Flight Control Team (FCT) roster shows the as-executed staffing plan for the ADCO console, including any substitutions or other changes that occurred after the staff scheduling spreadsheet was completed. This roster was used to count deviations, or swaps, from the planned schedule or to fill in any gaps to create a complete X matrix for analysis. Third, an email record was available from the group schedulers that documented the substitution requests from managers and operators.

The summary of this data is provided below in Table 8. The Y and M matrices – defining the workforce and the schedule rotation – are provided in Appendix E. Table 8 only shows the value of O as well as the number of gaps and number of swaps found from the historical data. The schedule rotation score and objective function score were then computed based on the historical schedule data.

For computation of the Schedule Rotation Score, the weekly rotation is not redesigned for each historical schedule period. Instead, the score (Equation 4) was calculated based on the design of the existing schedule rotation for that schedule period.

The inputs for the Schedule Rotation Score for each quarter are found in Appendix E. Table 9 shows a theoretical improved score if a different schedule rotation had been used.

For the Line of Work Construction step, the Y and M matrices were taken as a given from the historical schedule for each quarter. The C matrix had to be developed in order to calculate a solution for the objective function (Equation 16) for each schedule. The C matrix used in both the schedule comparison and the practical implementation is given below in Equation 17. These values for the C matrix were developed through discussion with ADCO group managers and schedulers.

$$C = \begin{bmatrix} 0.8 & 0.5 & 0.9 \\ 1 & 0.5 & 0.8 \\ 1 & 0.5 & 1 \\ 1 & 1 & 0.8 \end{bmatrix} \qquad \text{(Eq. 17)}$$

Table 8 shows the theoretical Schedule Rotation Score (Equation 4) and Schedule Score (Equation 16) for each historical schedule period. The results of the Shapiro-Wilk normality test is also provided for relevant datasets. The Shapiro-Wilk test found that for this dataset of n=16, the number of swaps and the schedule score for each quarter were distributed normally. However, the Schedule Rotation Score and the number of gaps in the schedule did not pass the normality test.

For values of N, D, W, and C used (same values used for all 16 schedules) the lowest possible Schedule Score is 191.1, while the highest possible is 273.

Note that for the number of operators for each schedule period (O) the value shown represents the number of operators who were actually scheduled using the legacy scheduling method. In many cases, additional operators were certified for the ADCO console but were not scheduled for any shifts (some were scheduled for on-call shifts). It is possible that some of these unused operators were not scheduled due to the limitations of the bottom-up scheduling legacy process, as discussed above in Theory. However, the exact reasons that each operator went unused are unknown. Therefore, only the used operators were counted.

Note also that the Y matrix data is omitted from Table 8 (although it is included in Appendix E). Changes in the Y matrix, especially the ratio of operators in each bucket who are available for scheduling, can have effects on all metrics shown below except for Schedule Rotation Score. These differences in the Y matrix are the reason that two quarters with the same value for O and the same Schedule Rotation (such as 2018 Q3 and 2018 Q2_ can have different resulting schedule scores. Analysis of the Y matrix and its effect on these results was not performed and is discussed in the Future Work section.

Table 9 shows improved results for all measures when the proposed process for Schedule Rotation selection and Line of Work Construction are used to create a new X matrix. Values for O, N, D, and W, Y, and C were taken as given. For the improved Schedule Rotation Score, an updated M matrix was used based on a new 8-operator rotation with a cost of 10. This same rotation was used for the 2019 Quarter 2 schedule in the practical implementation study. A different rotation was used in the 2019 Quarter 1 schedule due to challenges encountered during that schedule cycle.

For the Line of Work construction step, initially only the base constraints (Equations 9-12) were used to generate the X matrix and resulting Schedule Score (Equation 16). However, it was found with this method that some operators in the first bucket would be assigned as many as 45 days in a 91 day schedule. This shift load is considered impractical, as it does not allow time for those operators to accomplish other office tasks. An additional constraint was added limiting all operators to 21 shifts in the 91-day schedule period. This 21 day limit was based on historical constraints of limiting operators to three 7-day night shifts in a quarter. Table 9 includes the Schedule Score both with and without the 21-day limit implemented.

Table 8:
ADCO schedule data 2015-2018

Quarter	#Oper	Schedule Rotation Score*	#Gaps	#Swaps	Guideline Violations	Schedule Score**
2018 Q4	31	89.0%	11	67	9	215
2018 Q3	32	89.6%	29	85	8	209.5
2018 Q2	32	89.6%	4	57	3	216.1
2018 Q1	35	89.6%	28	48	6	211.8
2017 Q4	37	89.6%	0	54	2	207.6
2017 Q3	36	89.6%	3	108	3	206.6
2017 Q2	34	89.7%	11	30	5	204.2
2017 Q1	35	89.6%	5	62	1	202.4
2016 Q4	35	89.6%	1	51	7	204
2016 Q3	35	89.6%	0	76	4	203.3
2016 Q2	33	89.6%	3	55	5	205
2016 Q1	30	89.6%	2	54	7	209
2015 Q4	29	89.5%	0	60	3	215
2015 Q3	30	89.6%	0	56	3	214
2015 Q2	30	89.6%	6	48	5	213
2015 Q1	26	89.3%	13	26	9	214.8
Average	*33*	*89.54%*	*7.25*	*58.6*	*4.7*	*209.5*
Std Dev	-	*0.16%*	*9*	*19*	*2.4*	*4.7*
Normality	-	*<0.001*	*0.001*	*0.161*	*0.416*	*0.105*

**all quarters used the legacy ADCO 5-block rotation (score of 9.5) except for 2018 Quarter 4, which used the legacy ADCO 7-block rotation (score of 12.5)*

***For schedules with gaps, complete X matrix was based on FCT roster data for fill-in*

Table 9:
Improved metrics for 2015-2018

Quarter	#Oper	Rotation score	#Gaps	#Swaps	Guideline Violations	Model Score	Model Score (limit)
2018 Q4	31	91.0%	0	-	0	191.1	192.5
2018 Q3	32	91.1%	0	-	0	191.1	200.9
2018 Q2	32	91.1%	0	-	0	191.1	200.9
2018 Q1	35	91.3%	0	-	0	193.1	194.5
2017 Q4	37	91.4%	0	-	0	197.1	197.1
2017 Q3	36	91.3%	0	-	0	195.1	196.5
2017 Q2	34	91.2%	0	-	0	191.1	191.1
2017 Q1	35	91.3%	0	-	0	192.1	192.1
2016 Q4	35	91.3%	0	-	0	191.1	191.1
2016 Q3	35	91.3%	0	-	0	191.1	191.1
2016 Q2	33	91.2%	0	-	0	191.1	191.1
2016 Q1	30	90.9%	0	-	0	192.1	198.5
2015 Q4	29	90.8%	0	-	0	191.1	196.7
2015 Q3	30	90.9%	0	-	0	192.1	198.5
2015 Q2	30	90.9%	0	-	0	192.1	201.9
2015 Q1	26	90.3%	0	-	0	191.1	200.9
Average	*33*	*91.1%*	*0*	-	*0*	*192.1*	*196*
Std Dev	-	*0.27%*	*0*	-	*0*	*1.67*	*3.93*
Normality	-	*<0.001*	-	-	-	*<0.001*	*0.039*

ADCO Scheduling Case Study

The 2019 Quarter 1 schedule was completed on December 20th, 5 weeks prior to schedule start. As of the drafting of this results section, the 2019 Quarter 2 schedule process was in the on-call scheduling phase, scheduled to be completed and delivered by March 15th, 6 weeks prior to schedule start. The delay in delivery for 2019 Quarter 1 schedule is likely related to several challenges faced during the staff scheduling process, as discussed below.

2019 Quarter 1

The 2019 Quarter 1 schedule covered 91 days from mid-January to late April. The scheduling process started in October when group decision makers met to agree to use a process based on this study's framework and to select a schedule rotation and a set of constraints. A group briefing took place in early November with 6 weeks until the delivery deadline. However, the staff scheduling was delayed two weeks due to several reworks of the line of work generation step due to unexpected staffing changes. The planning phase began with 31 available operators but the first set of lines of work was delivered for 29 operators the week of Thanksgiving. Preference phase of staff scheduling was drawing to a close a week later when it was learned of an additional unexpected staffing change. This resulted in the process being reset. A new schedule rotation was selected for 28 operators and a new set of lines of work were generated following a pre-selection phase.

This final set of lines of work for Quarter 1 were generated with approximately one week left before the schedule delivery deadline, which was not sufficient time to complete staff scheduling on time, leading to the schedule being delivered one week late. On-call scheduling continued past the holidays but was eventually completed also with no gaps.

A final challenge faced during Quarter 1 scheduling was an unexpected staffing change after delivery of the schedule. Two operators carrying heavy shift loads would no longer be working console shifts. Thus, those shifts had to be distributed back to the rest of the workforce. Fortunately, a newly certified operator was available for shifts at about the same time, which prevented the number of swaps required to resolve the gaps from being even larger than they were. Regardless, the requirement for schedule deviation was not met for 2019 Quarter 1 due to this late personnel change.

2019 Quarter 2

The 2019 Quarter 2 schedule covered 84 days from late May to mid-July. The scheduling process started in January with debrief of Quarter 1, including a group discussion, a survey, and a meeting between group decision makers. Based on anonymous feedback from operators, an updated schedule rotation was designed for Quarter 2. Changes were made to adjust to the new distribution of the workforce (importantly, many fewer operators in lower-tiered buckets) and incorporate feedback on additional constraints to apply to improve work-life balance.

Following selection of a new schedule rotation, a lengthy pre-selection phase was conducted to schedule all operators in the lowest tier bucket and many of the operators in the top tier bucket. Following pre-selection, a complete set of lines of work were released for the remainder of the staff scheduling phase with 5 weeks until the delivery deadline. Quarter 2 has not encountered any significant challenges analogous to Quarter 1, and appears ready to be delivered on time and within specifications. However, data on operator satisfaction and schedule deviation remain pending.

Results

Table 10 contains data on the performance of the 2019 Quarter 1 and 2019 Quarter 2 ADCO scheduling process. Data is provided on the six performance measures (in bold) as well as 4 additional metrics that are useful for comparison to the solution comparison data in Tables 8 and 9. Results shown in bold red did not meet requirements. Results in bold Black did meet requirements. Results that are pending are listed as TBD.

Table 10:
Results from practical implementation

Performance measure or metric	**Requirement**	**2019 Quarter 1**	**2019 Quarter 2**
# Oper	-	28	28
Schedule Rotation Cost	-	10	10
Schedule Rotation Score	-	90.6%	90.6%
Schedule Score	-	203.5	213.4**
Performance measures with requirements			
Hours spent on schedule (by schedulers)	<15 hrs.	40 hrs.	16 hrs.
Deadline (date of delivery to calendars)	6 weeks early	5 weeks early	6 weeks early
Operator satisfaction (discrete/comments)*	>=75% satisfaction	72% (74%/60%)	81% (85%/57%)
Schedule completeness	0 gaps	0	0
Guideline violations	< 4 violations	5	3
Schedule deviation	<=15% swaps (<=41 for W*D=91)	78 swaps (29%)	TBD

**Quarter 1 had 89% response and Quarter 2 had 57% response*

***Quarter 2 was a 12-week instead of 13-week schedule. 12-week score of 197.4 multiplied by 13/12 to get simulated 13-week score.*

Analysis

The practical implementation results contain a sample size of only 2 completed schedules. It is no surprise that the results so far for that phase reveal the need for more data. Continued use on more schedule cycles will be needed to confirm that these new methods are quantitatively better than the legacy scheduling process and that requirements can be reliably met. The results from the theoretical solution comparison provide enough data to find evidence of significant improvement.

The qualitative impact of the new scheduling process is addressed in the Discussion and Conclusion sections. This Analysis section provides the results of statistical tests on the Rotation Score, the Schedule Score, and the performance measures from Table 9 and Table 10 as compared to the original schedule data in Table 8.

Rotation Score

The Rotation Score in the original schedule data had a mean of 89.5% with a standard deviation of 0.16%. The improved schedule solutions for those schedule periods with the same inputs had a mean Rotation Score of 91.1% with a standard deviation of 0.27%. An independent sample t-test shows that the difference in the means is significant with a 95% confidence interval no less than 1.4% improvement up to 1.7% improvement.

The Rotation Score for the two completed practical implementation schedule periods also show a statistically significant improvement, despite the low sample size. The 2019 results were both 90.6%, with a significant difference in the mean from the original schedule data on a 95% confidence interval that is no less than 0.8% improvement up to 1.3% improvement.

Schedule Score

The Schedule Score in the original schedule data had a mean of 209.5 with a standard deviation of 4.8. The improved schedule solutions for those schedule periods with the same inputs had a mean Schedule Score of 196.0 with a standard deviation of 4.0. An independent sample t-test shows that the difference in the means is significant with a 95% confidence interval no less than 10.2 points improved up to 16.7 points improved.

The Schedule Score for the two completed practical implementation schedule periods had a mean of 208.5 with a standard deviation of 7. The difference in the mean (which is only 1 point) was not shown to be statistically significant using an independent sample t-test.

Performance Measures

Only two of the performance measures can be statistically compared to the historical schedule data: guideline violations and schedule gaps. Reliable data was not available for the other four performance measures. See Discussion section below for a full discussion of these results, include those that were not statistically compared.

The guideline violation data must be understood in the context of how it was defined. Prior to the revision of the Schedule Rotation for the practical implementation study in 2019, the pervious schedule rotations allowed for operators to work through entire weekends and for 7 days straight of overnights. Under the older schedule rotations, guideline violations were defined as an operator not getting two consecutive weekends off after working a weekend or not getting a full week off of console assignment after any shift block. Following the revision of the schedule rotations for 2019 schedules, working more than 7 days in a row of night shifts and working through an entire weekend were added to the list of guideline violations. The data in Table 8 showing the guideline violations for the historical schedule data is based on the definition of guideline violation at the time If the new definition were used, the numbers would be upwards of 40 violations per schedule period.

The historical schedule data for Guideline Violations had a mean of 5 with a standard deviation of 2.5. The theoretical improved schedules had a consistent result of 0 guideline violations. This was shown to be a statistically significant improvement in the mean using an independent sample t-test. The 95% confidence interval started at no less than an improvement of 3.7 violations up to 6.2 violations.

The schedule gap data for the historical schedule data had a mean of 7.3 with a standard deviation of 9. This data was not shown to be normally distributed and had a wide distribution. The improved schedules from the theoretical solution comparison resulted in consistently completed schedules with no gaps. However, due to the uncertain nature of the original data, the independent sample t-test did not show that the difference in the mean was statistically significant. The 2019 results, with the smaller dataset, were also not shown to measurably improve the number of schedule gaps.

Discussion

The application of the improved staff scheduling framework was demonstrated to reduce guideline violations and schedule gaps to zero when applied to historical schedule data from the ADCO flight control group. The proposed framework, by design, should always publish a schedule with zero gaps. Therefore, while the comparison to historical data did not show a statistically significant improvement, it is expected that further trials will show that this is a true improvement to a baseline of zero schedule gaps per schedule period. The guideline violation data is not as numerically clear, given the number of violations seen in the 2019 implementation schedules. However, these guideline violations do not appear in the lines of work generated prior to the staff assignment process, as demonstrated by the lack of guideline violations in the theoretical data in Table 9. The guideline violations in 2019 Quarter 1 and 2019 Quarter 2 occurred by choice during staff scheduling when operators traded shifts to create more ideal lines of work to meet their preferences. The violations seen in these two schedules took the form of some operators working entire weekends or trading to work an extra shift or two some weeks. These violations were less severe than many instances of consecutive weekends of work seen in the historical data.

The measurable improvement in the Rotation Scores and Schedule Scores demonstrate that two key aspects of the proposed staff scheduling framework are effective in improving efficiency. First, the recommendation to re-evaluate and select a schedule rotation based on changes in personnel levels will measurably improve the flexibility of the rotation and availability of the workforce. Second, the recommendation to assign a cost to each type of operator and build a top-down set of lines of work based on minimizing that cost will measurably decrease the use of the more valuable operators while generating a fair schedule. Note that although this improvement in the Schedule Score was not born out in the 2019 schedule data, those results are confounded by recent decreases in available operators in the lower cost buckets, which has increased the possible minimum score that can be reached with the current workforce.

In addition to guideline violations and schedule completeness, operator satisfaction and schedule deviation were scored as top performance measures by the analysis summary in the House of Quality (Figure 17).

Operator satisfaction was measured via a debrief survey. The survey data was translated to a satisfaction score by averaging the percentage of positive and negative answers to each question in the debrief survey. Written comments in the survey were assessed for positive, negative, or neutral feedback. Neutral comments were counted as negative feedback. The complete set of survey data results are provided in Appendix C.

The subjective written responses from 2019 Quarter 1 indicate some growing pains with this new process. Only 60% of comments indicated a clear positive response to the new process. However, the total average satisfaction score missed the target value of 75% by only 3 points and the average score for non-comment responses met the target value. Quarter 2 survey responses show even more promising results, although the comment responses still missed the target value. Given the major issues with the legacy scheduling process, and that many of the "negative" comments from the survey constitute constructive criticism rather than flat out rejection of the new framework, these results indicate a step in a positive direction.

Schedule deviation documents how closely the executed roster plan was to the planned schedule, after the schedule period had passed. Per the data in Table 8, the historical average was to swap over 20% of all assigned shifts to a different operator. Historically, this results in even more personnel challenges such as task conflicts and guideline violations (which are not reported in the data compiled here). Minimizing these deviations will maximize the benefits of the scheduling process efficiencies. In 2019 Quarter 1, the number of schedule deviations exceeded the historical average. However, this number is inflated significantly by the unexpected departure of two operators who were carrying a heavy shift load. Nearly half of the deviations so far were to do the gaps created by this personnel change. When those 30 shifts are removed from the 78 deviations, the number of deviations drops to less than 18%, nearly within requirements. Clearly more data is needed to determine if the new scheduling process will make a measurable effect on this performance measure.

The remaining two performance measures had the lowest relative weight per the House of Quality in Figure 17. The schedule deadline was missed by 1 week in 2019 Quarter 1 and was met in 2019 Quarter 2. The hours spent on schedule requirement was exceeded by 250% in 2019 Quarter 1 but was met in 2019 Quarter 2. Many of the extra hours required in 2019 Quarter 1 can be attributed to many schedule redevelopment cycles due to several unexpected personnel changes that have already been described above.

Conclusions

Recommendations for NASA FOD

Scheduling practices for NASA's human spaceflight operations at the Mission Control Center in Houston can benefit from implementing several simple recommendations. Further research is needed to validate the full impact of the proposed staff scheduling framework on NASA FOD's 24/7 operations team. However, preliminary results indicate that the simple measures taken to apply top-down optimization techniques and cradle-to-grave process tracking has solved key problems that plagued at least one group of flight controllers staffing console for International Space Station operations. The following recommendations apply to all flight controller groups in FOD seeking to fill a multi-shift schedule within mission control. A subset of these recommendations may improve scheduling efficiency for single shift groups.

Recommendation 1 – Utilize Staff Scheduling Best Practices

As first discussed in Chapter 1, it was clear from a review of the existing scheduling practices in NASA FOD that scheduling concepts were internally developed and implemented, with little influence from prior research or literature. A thorough review of the staff scheduling literature reveals countless mathematical techniques for completing a staff schedule, developed over the past several decades. That research has converged over time on a simple 6-step framework outlined by Ernst, which addresses each decision that must be made to successfully generate a complete staff schedule. In addition to Ernst's process, the research has also converged on optimization techniques that solve the staff schedule as a top-down problem. In other words, the process is completed by ensuring the grid or schedule is filled in according to a set of constraints and by minimizing or maximizing some objective function.

These simple recommendations were applied to a case study of the flight controller scheduling problem, using data from 2015 to 2018. Not only were theoretically improved schedules produced by using these best practices, but two entire schedule development processes were also completed by applying a top-down optimization using Ernst's process: ADCO schedules for 2019 Quarter 1 and Quarter 2.

Many of the challenges faced under the legacy flight controller scheduling practices – schedule gaps, high numbers of deviations, overuse of senior operators, and frequent violations of constraints – have been shown to be solvable simply by utilizing a top-down optimization approach. These techniques have been borne out by repeated study in other industries and translate well to the environment of the Mission Control Center's 24/7 console staffing.

Recommendation 2 – Perform Stakeholder Analyses

Many of the concerns with the legacy flight controller scheduling process involved a lack of consideration for operator preferences. The schedule rotation in the ADCO group had been in use for many years without re-evaluation or discussion. It was unknown whether the approach to weekends and night shifts matched the work-life balance needs of a majority of operators. Lastly, the staff assignment process utilized a first-come first-serve method that was largely considered frustrating and unfair.

Anonymous surveys were used to gain insight into operator preferences as part of a stakeholder analysis, which is one of the first steps of any systems engineering process. This allowed several weaknesses in the existing process to be identified for modification in the new framework. Operators were again anonymously surveyed after each schedule period implementing the new framework. Preliminary results from the first schedule period show that a majority of operators find that the new scheduling framework meets their preferences more closely than the previous processes.

The stakeholder analysis also allowed for identification of the most important interests of all stakeholders, not just operators. By conducting a stakeholder analysis on managers, schedulers were able to obtain a better understanding of the goals of the scheduling process. In the case of the ADCO scheduling process, the list of stakeholder interests showed that "senior operator availability" was of high interest to managers. Therefore, a new process for developing schedule lines of work was developed that used an objective function geared specifically at balancing the needs of senior versus junior operators.

Stakeholder analyses are central to any systems engineering process. The insight they provide into the needs and preferences of all stakeholders is invaluable to ensuring the design of the system or process does not stray from those needs. All flight control groups within FOD should utilize a repetitive stakeholder analysis process to ensure that the scheduling processes is effectively meeting stakeholder needs. This recommendation can be implemented with or without the other recommendations provided.

Recommendation 3 – Performance Measure Tracking

As with stakeholder analyses, establishing performance measures and requirements is also central to all systems engineering process frameworks. In fact, many tools have been developed – such as the house of quality – specifically to provide easy visualization of the relationships between stakeholder interests, performance measures, and requirements. Tracking performance measures for any engineering project allows decision makers to assess if the system design is staying within specifications or if design iteration is needed. In the case of a staff scheduling process, these performance measures can be assessed after each schedule period to determine necessary changes for the next cycle.

The stakeholder analysis performed for the ADCO flight controller scheduling process allowed for the identification of six performance measures that together meet the interests of all stakeholders. Requirement values were set for these performance measures and measured for sixteen theoretical schedules and also for two schedule periods during the practical implementation study. The results of the six performance measures for these schedules revealed that the most difficult area to improve is with respect to schedule deviations, or swaps. The other requirements were largely met by the new process. Therefore, the process design for future schedule periods should focus on finding improvements that will minimize the post-delivery shift swaps between operators.

If performance measures and requirements are not continually tracked going forward, it will be impossible to provide an assessment of the effectiveness of the staff scheduling processes. A lack of accountability leads to stagnation, as was seen in the legacy flight controller scheduling process. All flight control groups in NASA FOD should adopt the process of tracking performance measures related to their console scheduling processes as an impetus for identifying areas for improvement.

Recommendation 4 – Schedule Rotation Adaptability

Under the legacy flight controller scheduling process, most flight control groups implement a single weekly schedule rotation that changes very little, if at all, from schedule to schedule or year to year. In spite of this lack of change, the workforce itself is very dynamic, with the ADCO group fluctuating from as few as 26 to as many as 36 operators over the last 5 years. Previously, little thought was put into whether the schedule rotation should adapt to fluctuations in the workforce. A method for evaluating the weekly schedule rotation for efficiency and flexibility was developed. Based on the scoring methods described here, it was shown that the effectiveness of a weekly schedule rotation changes depending on workforce size.

The results from both the schedule solution comparison and the practical implementation indicate that the previous ADCO weekly rotation was not the ideal rotation to meet the stakeholder interests. Improved weekly schedule rotations were selected from a large set of options using a randomization function developed in MATLAB. The improved weekly schedule rotations, which utilize smaller shift blocks and more operators per week, are a contributing factor to the increase in senior operator availability and reduction in schedule deviations.

All flight control groups in NASA FOD should take time to evaluate their current weekly schedule rotations and assess if stakeholder needs are being met by the current rotation. Measurable schemes for evaluating the weekly schedule rotation should be applied in order to compare options and select the best option that optimizes the performance measures of interest to each group.

Recommendation 5 – Design Staff Assignment Process

The staff assignment process is merely one step in Ernst's six-step framework for solving staff scheduling problems. However, this is a critical step as it is where the theory meets reality, as operators are schedule for actual shifts, impacting their personal calendar. The specific staff assignment process used in NASA FOD were found to vary widely when the legacy methods were identified for each flight controller group. A set of potential staff scheduling techniques were summarized above in Table 4. The pros and cons of each technique were discussed in the Theory section.

An updated staff assignment process was tested on the ADCO group during the practical implementation case study. The updated process eliminated unfair aspects of the legacy process (first-come first-serve) and allows operators some ownership of their schedules by allowing time for compromise and shift swaps during the conflict resolution phase. The updated process met expectations of efficiency by ensuring that schedules were delivered on time per the 6 week delivery requirement.

Anonymous debrief surveys indicated that the biggest improvement from the legacy scheduling process to the new framework was the fairness of the staff assignment step. Operators overwhelmingly found the new process fairer. Additionally, the lack of schedule gaps can partially be attributed to this change to the staff scheduling process, in addition to the top-down optimization techniques used to generate lines of work. The flexibility in the staff assignment process allowed operators to work together to find lines of work that everyone could support, leaving no gaps.

The effectiveness of the new staff assignment step is likely to ensure that this recommendation, more than any of the rest, will continue to be used in the ADCO flight control group moving forward. All other flight control groups should also assess their options for staff scheduling and select a new method that best aligns with their stakeholder interests.

Recommendation 6 – Match Work Guidelines to Occupational Health Research

A review of the occupational health research, particularly with regard to the effects of night shifts, revealed that the guidelines in use in NASA FOD to protect operators were somewhat at odds with the state-of-the-art recommendations. In addition to circadian effects, studies on safety and error risk showed that some commonly held assumptions in FOD regarding sleep shifting were not backed up by data.

In order to incorporate some of these lessons in the updated framework, a preference was given when selecting schedule rotations to select rotations that breakup the night shift week into at least two shift blocks, instead of the single 7-day shift block found in the legacy schedule rotation. This was found to meet stakeholder interests regarding flexibility, in addition to the health benefits.

NASA FOD should adopt new shift work guidelines that use up-to-date recommendations from the literature and take into consideration the results of several sleep studies that have been conducted on flight controllers, as discussed in the Literature Review above.

Generic Recommendations for Operations Researchers

Existing staff scheduling research is focused on minimizing cost or workforce size for common operations environments, such as nursing, power plant operations, or the service industry. Discussion of the flight controller scheduling problem for International Space Station operations reveals another type of staff scheduling problem that differs in many ways from the common problems explored in the literature. An exploration of how to solve this different kind of staff scheduling problem provides insight into weaknesses with the commonly applied staff scheduling framework. Recommendations are suggested for improving the generic framework. By applying these lessons from the flight controller staff scheduling case study, all staff scheduling solutions can benefit from an integrated view of the schedule design process.

Recommendation 1 – Design complete process

Existing staff scheduling research focuses on Ernst's six-step framework, which does not include steps for collecting inputs, iterating the process over-time, or tracking performance against requirements. By introducing systems engineering workflow concepts to the flight controller staff scheduling problem, it was shown that all of these missing steps can be integrated into Ernst's framework to provide context for the schedule design. Stakeholder analyses – both before and after a schedule cycle – allows for identification and tracking of the most important factors that make a well-designed schedule for each applicable case.

The distinction between good and bad inputs and constraints was notably absent from both the legacy flight controller scheduling process at NASA's FOD as well as the staff scheduling literature. By including operator preferences, opinions, and written feedback in the stakeholder analysis, the operators were given a say in the schedule design process. A majority of surveyed operators found the new process an improvement largely due to a perceived increase in fairness and flexibility of the schedule.

Systems engineering processes also advocate for identification, ranking, and tracking of performance measures. These performance measures should be tracked against established target requirement values. The use of performance measures was shown for the flight controller scheduling problem to provide indicators over time as to whether performance was improving or degrading. For example, the legacy ADCO scheduling process was increasing in the number of schedule gaps left in the published schedule until the new framework was applied, under the new framework, there have been no gaps in the published schedules.

By combining the well-established frameworks of staff scheduling design and systems engineering design, better staff scheduling solutions can be created for all problem types. These systems engineering concepts should be adopted by schedulers and researchers alike, allowing for all optimization solutions to staff scheduling problems to be developed with a broad perspective that accommodates stakeholder interests as well as design iteration during the implementation and maintenance phase. This would be an improvement over much of the currently published research on staff scheduling, which provides highly optimal mathematical tools for solving a schedule without any context.

Recommendation 2 – Validate Stakeholder Inputs

Recommendation 1 is not effective without ensuring good inputs are being provided in the stakeholder analysis step. Recommendation 2 is to find methods to validate the assumptions from schedulers and managers. Much of the current staff scheduling literature provides optimization techniques in order to minimize workforce size while meeting stakeholder requirements. However, methods of checking these requirements for validity are not addressed.

In the flight controller scheduling case study, a potential scheme for scoring the details of the schedule rotation was proposed and compared to the legacy schedule rotation. Using this scheme, it was shown that the legacy schedule rotation was deficient at adapting to certain needs of the schedule designers. The scoring scheme allowed a concrete way to measure and compare options and select the best schedule rotation based on the stakeholder interests which were collected during the stakeholder analysis. The increased flexibility of a new schedule rotation, which was selected using this scheme, resulted in fewer schedule deviations when the new process was implemented.

Validating stakeholder assumptions, inputs, and requirements – as with the schedule rotation scoring scheme – is vital to ensuring that a schedule solution does not optimize to parameters that do not actually impact the performance characteristics of interest. Researchers designing staff scheduling solutions should include in their framework a step or technique to ensure that the requirements provided are relevant to the problem. In the absence of such a technique, the inputs may simply be based on the instincts of managers and decision makers. Optimizing in such a framework may not actually be optimal at all.

Recommendation 3 – Consider Occupational Healtlh in Case Studies

As part of the effort to put any staff scheduling solution into context, designers should also consider the field of occupational health; in particular, the state-of-the-art of recommendations relating to sleep and night shifts. The connection between circadian rhythm and negative outcomes during night shift work are well established in the occupational health literature. By not designing schedules that take these affects into account, schedule designers accept risk both to the efficiency of the work as well as to the health of the operators.

While reviewing the existing recommendations for night shift work in the literature, it was found that the legacy scheduling process in NASA FOD only partially accounted for some of these best practices. While guidelines existed to limit total shift work on an employee-by-employee basis, most groups were having operators work as many night shifts in a row as possible (up to 7 days), which contradicts research that shows that extended days on nights does not necessarily reduce errors.

Using operator survey data from the stakeholder analysis, existing FOD guidelines, and the best practice recommendations from the occupational health field, an updated set of guidelines and constraints were used to design healthier schedules for the ADCO flight controller group. Integration of this additional field of research is essential if schedulers wish to reduce risk, not just cost.

Recommendation 4 – Explore Wider Range of Optimization Goals

The literature reviewed on staff scheduling problems showed a consensus among researchers that the goal of the schedule design and optimization process is to minimize cost of the schedule. This cost is often measured in workforce size – be it the total workforce size of the organization or the workforce required to complete the schedule over a given period of time. In contrast to this consensus, the flight controller scheduling problem within NASA FOD presents an entirely different cost model.

With constant demand (one person per console per shift) and a majority percentage of workload performed off console, the size of the flight controller workforce is minimally impacted by changes to the scheduling process. Therefore, in order to adapt staff scheduling best practices to the flight controller scheduling problem, an objective function was developed that seeks to optimize the cost to *experience* rather than total workload. This objective function, when compared to the legacy schedules, showed a marked improvement over the number of senior operators required to fulfill the schedule. Based on the stakeholder analysis, saving senior operator time for other tasks was far more valuable to managers than reducing the size of the workforce.

The flight controller scheduling problem is surely not unique in the relationship between workforce size and the scheduling process. Rather than focus on more advanced mathematical methods for solving the schedule cost problem faster, researchers should also devote time to identifying alternate types of cost associated with staff schedules. In addition to cost of senior operators and workforce size, other types of cost could include: risk of error, total errors, lost time, health effects, or efficiency. Objective functions for measuring these costs will depend on lessons learned from implementing the other recommendations above. Having options for optimization goals will make the staff scheduling techniques found in the literature more adaptable for various types of problems.

Future Work

Limitations

Several limitations with this study warrant future work. As has been shown in Chapter 1, there is an extensive list of available optimization techniques that can be applied to solve a staff scheduling problem. Only one of these techniques was tested in this study – the COIN Branch and Cut (CBC) solver from OpenSolver. The recommendations made above are independent of the solver used. However, it is possible that a comparison of ILP solvers might identify some advantages to certain solvers over others to improve this framework further.

How to conduct workforce planning is an important open question for the NASA FOD application of this framework. Under the current paradigm, flight controller workforce size is not directly affected by changes to the staff scheduling process. However, lessons learned regarding shift load, ideal days off constraints, and senior operator use in the schedule may reveal an ideal ratio of senior to junior operators. Flight control groups already carry “red/yellow/green” target numbers that are reported to senior management. These targets could potentially be adjusted based on new data from the improved console shift scheduling process.

Related to workforce planning is the problem of the dynamic size of the workforce in the data used in the case study. Over the course of 2015 through 2019, the size of the overall workforce fluctuated from as low as 26 to as high as 36. In particular, the number of operators in the lowest tiered bucket ranged from 2 to 6. These differences can greatly impact the scoring results for the objective function when solving for a complete set of lines of work. Further data analysis is warranted to assess the effectiveness of the updated framework depending on the workforce demographics. Furthermore, data analysis should be conducted in an attempt to draw correlations between specific changes to the staff scheduling process and the performance measure outcomes. Without this additional analysis, it is difficult to assess specifically which changes have improved performance and have had no effect or even a negative effect on performance.

Lastly, the process applied in the practical implementation case study in 2019 should continue through 2019 and beyond, with data recorded from debrief surveys and performance measure results. The current dataset based on two schedule periods is insufficient to declare victory with the improved process. Additional schedule periods will help find the signal in the noise, especially considering the very dynamic period of personnel change seen in the ADCO group during the study period.

Refine Design

The opportunities to improve the design of a staff scheduling process are as many as there are steps in the process. The current framework is merely a starting point for the concept of merging the worlds of systems engineering and staff scheduling research. Future work will likely change much of the details of what has been presented. Below are a few suggestions for where to start.

The gap in the framework that is most frequently pointed out is that the on-call scheduling of flight controllers was done separately from the shift line of work assignments. While this process has worked sufficiently in the 2019 implementation in the ADCO group, the on-call scheduling is decidedly not optimized or top-down. So far, no gaps have occurred with the current process, but there is some frustration with having to do two rounds of preference selection and conflict resolution to resolve first the shift lines of work and then the on-call shifts. Updating the variable matrix and constraints in the solver to account for on-call shifts in addition to console shifts is a natural next step.

Another update to the variable matrix and constraints involves the rigidity of constraints. Within the current design, all constraints added to the solver are treated as hard constraints and cannot be broken. In practice, there is often a distinction between hard and soft constraints, with soft constraints being preferred but not mandatory. Ernst suggests a strategy in which soft constraints are allowed to be broken, but incur a penalty cost. An update to the objective function used to design the lines of work could account for penalty costs and allow more flexibility with results.

Another method that could allow flexibility in the results would be to replace the OpenSolver-in-Excel paradigm with a less rigid tool that allows for the display of multiple valid solutions, rather than the single optimal solution. With the simple objective function and constraints utilized in the framework, there are many line of work solutions that result in the same minimum cost score. Having access to view and select from all of the schedule solutions that produce the minimum score would give schedulers an advantage when picking a set of lines of work to send out to their group for the staff assignment phase.

The OpenSolver-in-Excel paradigm also has a learning curve when trying to update the matrices from a change in workforce size or constraints. Either another tool should be used or a user-friendly GUI should be developed that allows for a user to answer simple queries such as “How many operators?”, and have the matrices auto-generated for the solver.

The staff scheduling process is the step in the staff scheduling process that has the most impact on the operators. Innovation should continue to occur in this area to ensure that lines of work are assigned to individual operators in a clear and fair way that does not alienate the workforce through miscommunication. One improvement to the staff scheduling step that is already being implemented in the 2019 Quarter 3 schedule in the ADCO group is to use a cost function to optimize tie-breaking between conflicting operator preference inputs.

Further FOD Implementation

The recommendations above present a challenging set of next steps for NASA FOD schedulers. The new framework is currently only in use in a single flight controller group. At least half a dozen other 24/7 operations consoles can benefit from these recommendations. A white paper should be prepared and taken on a road show of flight controller groups and leadership personnel to make a case for implementation.

As the process continues to be used in ADCO, further lessons will be learned and the process design will be refined. To prevent each group from duplicating work, a flight controller scheduling cadre should be established to share lessons across groups and benefit from the different perspectives. Note that several differences between groups, such as workforce makeup, certification levels, non-console tasking, etc. will make their specific scheduling problems dissimilar and provide discussion points for comparison.

This flight controller scheduling cadre will reveal other opportunities for implementation such as expanding use cases to include on-call scheduling, MPSR console scheduling, and simulation scheduling into the decision variable matrices. Through expanding the inputs and constraints of the framework, the proposed process should be capable of enveloping all FOD roles that rely on a rotating duty schedule.

Lastly, FOD should build on the research previously conducted within the organization – such as with Harvard sleep study – and gather more data on the performance of their operators on shift work. The command error database should be updated to take more precise data on the time that errors occurred. It may be useful to also expand the questions regarding consecutive days at work to distinguish between console work and off-console work. FOD should also look into doing its own sleep study to understand the frequency of Shift Work Sleep Disorder (SWSD) in the population.

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APPENDIX A:

NASA HISTORY

NASA's First Generation of Flight Directors

Name	**Class**		**Color**	**Notable Missions**
Chris Kraft	1960		Red	Project Mercury (All)
John Hodge	1963		Blue	Gemini 8
Gene Kranz	1963		White	Gemini, Apollo (several)
Glynn Lunney	1963		Black	Apollo (several)
Cliff Charlesworth	1966		Green	Apollo (several)
Gerald Griffin	1968		Gold	Apollo 10
Milt Windler	1968		Maroon	Apollo 14
Pete Frank	1968		Orange	Apollo 12, Apollo-Soyuz
Phil Shaffer	1971		Purple	Skylab
Donald Puddy	1971		Crimson	Skylab
Neil Hutchinson	1971		Silver	Apollo-Soyuz
Charles Lewis	1971		Bronze	Apollo 17

(Appendix continued on next page)

Foundations of Mission Operations [30]

1. To instill within ourselves these essential qualities of leadership in pursuit of technical and professional excellence...

Discipline...Being able to follow as well as to lead, knowing that we must master ourselves before we can master our task.

Competence...There being no substitute for total preparation and complete dedication, for space will not tolerate the careless or indifferent.

Confidence...Believing in ourselves as well as others, knowing that we must master fear and hesitation before we can succeed.

Responsibility...Realizing that it cannot be shifted to others, for it belongs to each of us; we must answer for what we do, or fail to do.

Toughness...Taking a stand when we must; to try again, and again, even if it means following a more difficult path.

Teamwork...Respecting and utilizing the abilities of others, realizing that we work toward a common goal, for success depends upon the efforts of all.

Vigilance... Always attentive to the dangers of spaceflight; Never accepting success as a substitute for rigor in everything we do.

2. To always be aware that suddenly and unexpectedly we may find ourselves in a role where our performance has ultimate consequences.

3. To recognize that the greatest error is not to have tried and failed, but that in the trying we do not give it our best effort.

APPENDIX B:

ISS FLIGHT CONTROL TEAM

Flight Control Team Description

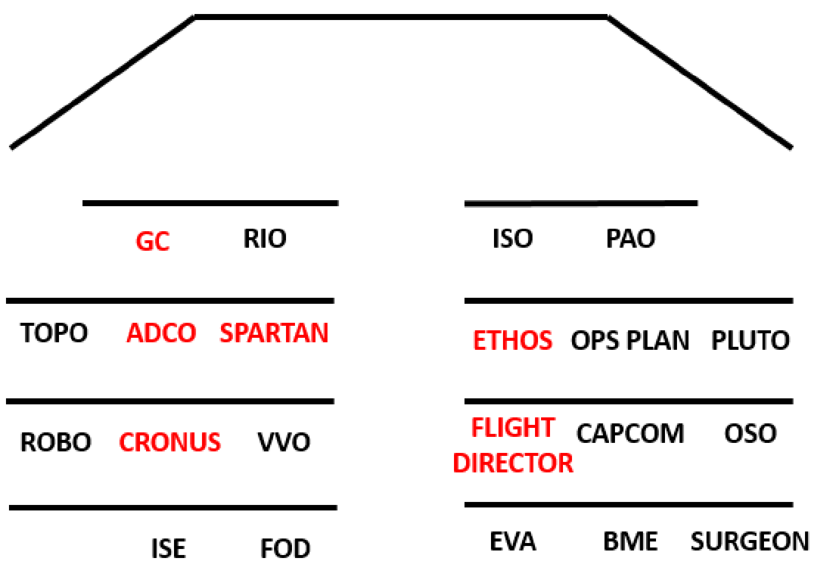
The ISS Flight Control Team (FCT) that operates from MCC in Houston is made up of 6 to 21 front room positions. The FCT operates from Flight Control Room-1 (FCR-1), a control room first used during the Apollo Program for the Apollo 7 test flight. The second of the two control rooms that were used for Apollo, Mission Operations Control Room-1 (MOCR-1) is located on the floor above FCR-1 and has been decommissioned – now preserved as a National Historic Landmark. FCR-1 consists of four rows of consoles to accommodate up to the maximum 21 flight controllers for the highest ops tempo shifts, such as vehicle rendezvous or spacewalk operations.

ISS FCR-1 during Cygnus vehicle departure, February 2019 (Photo credit: NASA https://twitter.com/NASA_Johnson/status/1093926356063322112)

(Appendix continued on next page)

The FCT can also scale down to a skeleton crew for low tempo shifts, such as weekends or crew sleep periods. The skeleton crew consists of just six flight controllers who staff the consoles 24/7, every day of the year. Those flight control positions are GC, ADCO, SPARTAN, CRONUS, ETHOS, and the Flight Director.

These are the flight controllers whose duties have direct responsibility for the safety of the on-orbit crew and the ISS vehicle itself. These duties are so crucial to the mission, in fact, that for several days during Hurricane Harvey in August 2017, the FCT hunkered down in MCC and never left, surrounded by rising flood waters.



ISS Flight Control Team layout in FCR-1

These six flight control disciplines (highlighted in red in the above diagram) were surveyed to understand their console scheduling processes and practices.

(Appendix continued on next page)

Flight Control Team Scheduling Practices

Provided is a detailed summary of the various practices used by the other flight control groups surveyed during the stakeholder analysis. Some notable differences between these groups and ADCO group were found and are highlighted below.

Group B

Group B uses the weekly schedule rotation in the figure below.

	Mon	Tues	Wed	Thurs	Fri	Sat	Sun
N	<-J1	J1	J1	J1	J1	J2	J2->
D	J3	J3	J3	J3	J3	J4	J4
A	J6	J6	J6	J6	J7	J7	J7

Group B only uses two buckets – operators and specialists. Their operators work all of the Afternoon and Night shifts. They balance shift load by trying to have 2-3 weeks between an operator's two shift blocks. They do not use quotas (i.e., no limit to number of shifts per quarter) and do not take operator preferences into account. Shift allocation is fully managed by the schedulers and manager.

Group C

Group C uses the weekly schedule rotation in the figure below.

	Mon	Tues	Wed	Thurs	Fri	Sat	Sun
N	<-J1	J1	J1	J1	J1	J2	J2->
D	Day shift is not a consistent pattern						
A	<-J3	J3	J3	J3	J4	J4	J4->

Group C uses 3 buckets and there is a shift quota per bucket. The manager's do the staff assignment but operator preferences are taken into account in the scheduling process.

Group D

Group D has no standard weekly rotation. Individual shifts are selected by volunteer allocation on a day-by-day basis. Group D does use a few bucket definitions that include shift quotas over the 6-month schedule period.

Group E

Group E uses the weekly schedule rotation in the figure below.

	Mon	Tues	Wed	Thurs	Fri	Sat	Sun
N	J1	J1	J1	J1	J1	J2	J2
D	J3	J3	J3	J3	J3	J4	J4
A	J5	J5	J5	J5	J5	J6	J6

Group E is the only group surveyed that uses team assignments. Team assignment means that the same three operators are assigned to work the Day, Afternoon, and Night shifts together on the same day. The team will work the same weeks in the schedule period. The teams do not work back-to-back weeks. The schedule period is smaller, on the order of a month instead of a quarter.

Group F

Group F uses the weekly schedule rotation in the figure below.

	Mon	Tues	Wed	Thurs	Fri	Sat	Sun
N	<-J1	J1	J1	J1	J1	J2	J2->
D	J3	J3	J3	J3	J3	J4	J4
A	J5	J5	J5	J5	J5	J6	J6

Group F staff assignment is done by managers, but the process allows operator preferences. The schedule period is quarterly, except for the second half of the year, which is done in a 6-month drop in order to have holiday schedules done sooner.

APPENDIX C:

FLIGHT CONTROLLER SURVEY DATA

Flight Controller Survey Data

Stakeholder Survey Data

Group	Bucket	Preferred shift	Second pref	Shift set	Weekend 1	Weekend 2	Rotation?	Repeat	Sleep shifting	Nights
A				2 to 5	Free		No	7	1	4 to 7
A				2 to 5	Whole		No	7	1	4 to 7
A				2 to 5	Whole		No	7	1	4 to 7
A				Special	Free		No	7	2	4 to 7
A				Special	Whole		No	7	2	1 to 3
A				2 to 5	Whole		No	7	2	1 to 3
A				2 to 5	Free		No	7	3+	8 to 10
A				2 to 5	NP		No	7	3+	4 to 7
A				2 to 5	Whole		No	7	3+	4 to 7
A				2 to 5	Whole		No	7	3+	8 to 10
A				2 to 5	Whole		Yes	7	2	1 to 3
A				6 to 7	Free		No	10	2	8 to 10
A				2 to 5	Whole		Yes	14	2	1 to 3
A				2 to 5	Free		No	30	0	1 to 3
A				2 to 5	Free		No	30	2	1 to 3
A				2 to 5	Free		No	NP	1	1 to 3
A				2 to 5	Special		No	NP	1	8 to 10
A				6 to 7	Free		No	NP	2	4 to 7
A				2 to 5	Whole		No	NP	2	1 to 3

Group	Bucket	Preferred shift	Second pref	Shift set	Weekend 1	Weekend 2	Rotation?	Repeat	Sleep shifting	Nights
A				Special	Free		No	NP	3+	1 to 3
A				2 to 5	Free		No	NP	3+	1 to 3
A				2 to 5	Free		Yes	NP	1	4 to 7
A				2 to 5	Free		Yes	NP	2	4 to 7
A				2 to 5	Free		Yes	NP	2	Special
B	2	3	2	2 to 5	Whole	Only	No		0	1 to 3
B	2	2	3	2 to 5	Whole	Only	No		1	4 to 7
B	3	3	2	2 to 5	NP	Only	No		2	4 to 7
B	2	2	3	2 to 5	Free	Only	No		2	1 to 3
B	1	2	3	2 to 5	Free	Only	No		2	1 to 3
B	3	2	3	2 to 5	Whole	Only	No		3	1 to 3
C		2	2	2 to 5	Free	Only	No		3	4 to 7
B	1	2	3	2 to 5	Free	Set	No		2	4 to 7
C		2	3	6 to 7	Whole	Set	No		2	1 to 3
B	2	1	2	6 to 7	Free	Set	No		3	4 to 7
C		2	1	2 to 5	Whole	Set	No		3	4 to 7
C		1	3	6 to 7	Whole	Set	No		3	4 to 7
C		3	1	2 to 5	NP	Set	No		3+	1 to 3
C		2	3	2 to 5	Whole	Set	No		3+	4 to 7
B	2	3	2	2 to 5	Free	NP	NP		1	4 to 7
B	3	3	2	2 to 5	NP	NP	NP		1	1 to 3
B	1	2	3	2 to 5	Free	Set	NP		1	4 to 7
B	1	3	2	2 to 5	NP	Set	NP		2	1 to 3
B	3	2	3	2 to 5	Whole	NP	Yes		2	4 to 7
B	1	2	3	2 to 5	Whole	Only	Yes		2	4 to 7

Group	Bucket	Preferred shift	Second pref	Shift set	Weekend 1	Weekend 2	Rotation?	Repeat	Sleep shifting	Nights
B	2	2	1	2 to 5	Whole	Set	Yes		1	4 to 7
C		2	1	6 to 7	Whole	Set	Yes		2	4 to 7
B	3	2	3	2 to 5	NP	Set	Yes		3+	4 to 7

Debrief Survey Questions

1. What bucket were you in for Quarter 1 2019 scheduling?
   a. Operator
   b. Specialist
   c. MCG
   d. Augment
2. How would you rate the efficiency of the scheduling process used for Quarter 1?
   a. Took more time than previous quarters
   b. Took the same amount of time as previous quarters
   c. Took less time than previous quarters
3. How many hours did you spend on Quarter 1 scheduling (reviewing schedule, providing preferences, resolving conflicts, etc.)? Please estimate to the nearest half-hour.
4. Do you believe the process used for Quarter 1 scheduling adapted well to the changing personnel levels?
   a. More flexible than previous methods
   b. Similar flexibility to previous methods
   c. Less flexible than previous methods
5. How would you rate the fairness of the scheduling process used for Quarter 1?
   a. More fair than previous methods
   b. About the same fairness
   c. Less fair than previous methods
6. Was the schedule for night shifts you were assigned fair as far as leaving time for sleep-shifting? (i.e., enough time between shift sets to sleep shift or take time off)
   a. I was not assigned night shifts (O1s)
   b. Spacing of night shifts was fair
   c. Spacing of night shifts was not fair (please specify)
7. If you could choose the scheduling method for future quarters, which would you choose?
   a. Legacy ADCO method (choose shift blocks in first come first serve)
   b. New ADCO method (select a line via preferences)
   c. Other (please specify)
8. Please rank the criteria below based on how important they are to you in a scheduling method.
   a. Schedule is complete with no gaps.
   b. Shift selection process is fair.
   c. Sufficient flexibility is provided for personal leave/preferences.
   d. Management defined constraints are met (e.g., number of IFCs working a week, certain buckets working only certain types of shifts, etc.)
   e. Night shift assignments are fair and supportable (sufficient time to recover, not too many or too few, etc.)
9. How do you feel about the number of shifts you were assigned for Quarter 1 2019?
   a. Too few shifts
   b. About the right number of shifts
   c. Too many shifts
10. Please provide any other comments you have regarding the scheduling process. What other factors are most important to you?

Debrief Survey Data – Quarter 1

	Type	Time	Hrs.	Flex	Fair	Nights	Method	Ranking	Shifts	Comments
1	MCG	More	1	More	More	N/A	New	4,2,1,5,3	About right	N/A
2	Oper	More	1.5	Same	Same	Fair	Old	2,3,5,1,4	Too many	Neg
3	Oper	Less	2	Same	More	Not fair	Other	4,3,1,5,2	About right	Neg
4	Oper	Less	1	More	More	Fair	New	2,4,3,1,5	Too many	Neg
5	Spec	More	1.5	Same	More	Fair	Other	4,2,3,5,1	About right	Pos
6	MCG	More	0.5	More	More	N/A	New	4,1,3,5,2	About right	N/A
7	Spec	More	2	Less	More	Fair	New	4,2,3,5,1	About right	N/A
8	Aug	More	0.5	Same	Same	N/A	New	5,1,2,4,3	Too few	Neg
9	Aug	Less	2	More	More	N/A	New	4,1,2,3,5	About right	Pos
10	Aug	More	4	Same	Same	N/A	Old	3,1,4,5,2	Too many	Neg
11	Aug	Less	2	Same	More	N/A	New	5,3,2,4,1	Too few	N/A
12	Aug	Same	1.5	Less	More	N/A	Other	5,2,1,4,3	Too many	Pos
13	Aug	More	4	More	More	N/A	New	3,1,2,5,4	About right	N/A
14	MCG	Same	4	Less	More	N/A	New	4,2,1,3,5	About right	Pos
15	Aug	More	30	Same	Same	N/A	New	4,2,1,3,5	About right	Pos
16	MCG	More	3	More	Same	N/A	New	5,3,1,4,2	Too few	Pos
17	Spec	More	3	Same	More	Fair	N/A	4,2,1,5,3	About right	Pos
18	MCG	Same	0.5	More	Less	N/A	New	4,5,3	About right	Pos
19	MCG	Same	1	More	More	N/A	N/A	4,3,1,2,5	About right	N/A
20	Aug	More	0.5	Less	Same	N/A	N/A	5,2,4,1,3	Too many	Neg
21	Aug	More	1	Same	More	N/A	New	5,3,1,2,4	About right	N/A
22	Spec	Less	3	Less	Same	Fair	Other	2,3,5,1,4	About right	N/A
23	MCG	More	1	Same	More	N/A	New	5,3,2,4,1	About right	N/A
24	Spec	More	1	More	More	Fair	New	3,2,4,1,5	About right	Pos
25	MCG	Less	1.5	More	More	N/A	New	1,3,4,2,5	About right	N/A

Debrief Survey Data – Quarter 2

	Type	Time	Hrs.	Flex	Fair	Nights	Method	Ranking	Shifts	Comments
1	MCG	less	1	more	fair	fair	New	N/A	About right	N/A
2	Spec	less	1	same	fair	fair	New		About right	Pos
3	Oper	same	1	more	fair	fair	New		About right	Pos
4	Aug	less	0.5	same	fair	n/a	New		About right	N/A
5	MCG	more	1	same	fair	fair	New		About right	Neg
6	Spec	more	3	less	fair	fair	New		Too few	N/A
7	Spec	more	1.5	same	fair	fair	Old		Too few	N/A
8	Aug	same	0.5	same	fair	n/a	New		About right	N/A
9	Aug	more	2.5	less	fair	n/a	Old		About right	N/A

APPENDIX D:

EXAMPLE SCHEDULING PROBLEM

Example schedule showing cascade problem with 5 teams on a 9 day schedule period

1.	X	X	X	O	Y	Y	Y	O	Z
2.	O	Y	Y	Y	O	Z	Z	Z	O
3.	Y	Z	Z	O	X	X	X	O	Y
4.	Z	O	O	X	O	O	O	Y	O
5.	O	O	O	Z	Z	O	O	X	X

Assume the following:

- Must take a break after 3 days
- Must have day off before switching shifts
- Cant shift backwards

Say team 5 can't work the last day and needs to swap shifts. There are no potential swaps that do not require more than one other team to also swap shifts. For example in the options below which are single day swaps, the two constraints are violated:

EXAMPLE 1

1.	X	X	X	O	Y	Y	Y	O	Z
2.	O	Y	Y	Y	O	Z	Z	Z	O
3.	Y	Z	Z	O	X	X	X	O	Y
4.	Z	O	O	X	O	O	O	Y	X
5.	O	O	O	Z	Z	O	O	X	O

EXAMPLE 2

1.	X	X	X	O	Y	Y	Y	O	Z
2.	O	Y	Y	Y	O	Z	Z	Z	X
3.	Y	Z	Z	O	X	X	X	O	Y
4.	Z	O	O	X	O	O	O	Y	O
5.	O	O	O	Z	Z	O	O	X	O

In example 3, two days are swapped with team 4 in order to meet constraints

EXAMPLE 3

1.	X	X	X	O	Y	Y	Y	O	Z
2.	O	Y	Y	Y	O	Z	Z	Z	O
3.	Y	Z	Z	O	X	X	X	O	Y
4.	Z	O	O	X	O	O	O	X	X
5.	O	O	O	Z	Z	O	O	Y	O

The cascade effect is often encountered when manually completing a large scheduling problem. The effect presents itself when nearing the end of the scheduling and the remaining several squares/gaps/holes need to be completed, but there remains no feasible solution. This occurs due to the scheduler being unable to foresee the outcome of their earlier scheduling decisions.

In example 5 below, the scheduler chose to keep teams 1-3 on the same shift for the entire schedule, rather than shift them forward after the breaks. Teams 4 and 5 are needed to complete the missing shifts on days 1, 4, 5, 8, and 9. There are a total of 7 gap shifts.

1.	X	X	X	O	X	X	X	O	X
2.	Y	Y	Y	O	Y	Y	Y	O	Y
3.	O	Z	Z	Z	O	Z	Z	Z	O
4.	O	O	O	O	O	O	O	O	O
5.	O	O	O	O	O	O	O	O	O

In step 1 below, team 4 can fill in 3 of the gaps.

1.	X	X	X	O	X	X	X	O	X
2.	Y	Y	Y	O	Y	Y	Y	O	Y
3.	O	Z	Z	Z	O	Z	Z	Z	O
4.	Z	O	O	X	O	O	O	X	O
5.	O	O	O	O	O	O	O	O	O

However, team 5 can now only fill 2 of the remaining 5 gaps. The two remaining gaps, shown in red, require someone to fill in shift Z. None of the teams can support this shift without violating a constraint.

1.	X	X	X	O	X	X	X	O	X
2.	Y	Y	Y	O	Y	Y	Y	O	Y
3.	O	Z	Z	Z	O	Z	Z	Z	O
4.	Z	O	O	X	O	O	O	X	O
5.	O	O	O	Y	O	O	O	Y	O

Swap 1 below (swaps shown in green) resolves the second gap.

1.	X	X	X	O	X	X	X	O	X
2.	Y	Y	Y	O	Y	Y	Y	O	Z
3.	O	Z	Z	Z	O	Z	Z	Z	O
4.	Z	O	O	X	O	O	O	X	O
5.	O	O	O	Y	O	O	O	Y	Y

However the gap on day 5 remains. No solutions exist with a single shift swap that will complete this schedule. Manual trial-and-error will result in several shift swaps or violating at least one constraint. The example below solves the problem with several swaps (in green) but team 5 is violating the shift forward only constraint.

1.	X	X	X	O	X	X	X	O	X
2.	Y	Y	Y	O	Y	Y	Y	O	Z
3.	O	O	Z	Z	Z	O	Z	Z	O
4.	Z	Z	O	X	O	O	O	X	O
5.	O	O	O	Y	O	Z	O	Y	Y

Additional swaps would be needed to find a viable solution with no constraint violations.

1.	X	X	X	O	X	X	X	O	Y
2.	Y	Y	Y	O	Y	Y	Y	O	Z
3.	O	O	Z	Z	Z	O	Z	Z	O
4.	Z	Z	O	X	O	O	O	Y	O
5.	O	O	O	Y	O	Z	O	X	X

Resolving these kinds of dilemmas is time consuming. Schedulers may often find that there are no feasible solutions, if they are working around personal leave calendars in addition to the shift rotation constraints.

This manual method can be described as bottom-up. Implementing a top-down scheduling approach, which addresses all constraints in each decision of the scheduling process, is therefore preferred.

APPENDIX E:

DETAILED RESULTS

Schedule Rotation Inputs

Workforce Numbers per Quarter

Quarter	Bucket 1	Bucket 2	Bucket 3	Bucket 4
2019 Q2	2	8	7	11
2019 Q1	2	7	8	11
2018 Q4	4	6	14	7
2018 Q3	2	7	14	9
2018 Q2	2	11	9	10
2018 Q1	4	6	13	12
2017 Q4	5	12	8	12
2017 Q3	4	8	14	10
2017 Q2	6	6	12	10
2017 Q1	3	15	10	7
2016 Q4	7	9	9	10
2016 Q3	7	14	14	
2016 Q2	5	14	14	
2016 Q1	3	13	14	
2015 Q4	3	12	14	
2015 Q3	3	13	14	
2015 Q2	2	13	15	
2015 Q1	2	12	12	

M-Matrix Data

$$M_1 = \begin{bmatrix} 7 & 0 & 0 & 0 & 0 \\ 0 & 5 & 2 & 0 & 0 \\ 0 & 0 & 0 & 4 & 3 \end{bmatrix} \text{(used 2015 Q1 to 2018 Q3)}$$

$$M_2 = \begin{bmatrix} 4 & 3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 3 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 4 & 3 \end{bmatrix} \text{(used 2018 Q4)}$$

$$M_3 = \begin{bmatrix} 7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 3 & 2 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 2 & 3 & 2 \end{bmatrix} \text{(used 2019 Q1)}$$

$$M_4 = \begin{bmatrix} 5 & 2 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 3 & 2 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 4 & 3 \end{bmatrix} \text{(used 2019 Q2)}$$

APPENDIX F:

SHIFT ROTATION MATLAB SCRIPT

Random Schedule Generator Function

```
function [schedules,M,I] =
schedule_creator_final(numdays,maxdays,numweeks,numsched,switchfactor,certs)

%How to use schedule_creator_final
%provide inputs as schedule_creator(numdays,maxdays,numsched)
%numdays       W*D - how many days the repeating schedule should cover
%maxdays       max consecutive days each person should work
%numweeks      W - number of sub-periods in the schedule
%numsched      how many random schedules to create
%switchfactor  rotation cost for switching operators
%certs         O - number of operators available to schedule

%Note that the following are not inputs
%N     number of shifts per day
%D     number of days in the sub-period

%They are omitted because the use case for this study was the NASA flight controller scheduling problem,
which always has N = 3 and D = 7. Therefore, maxscore (MP) which is necessary to compute a rotation
score, is calculated simply based on certs (O):

maxscore = (certs-3)*5+7*3;

%Create initialization matrix for later use

shifts = zeros(3,numdays);

%Schedules will be saved in a structure as follows.
%   schedules(n).holes       a matrix that says if all shifts are filled
%   schedules(n).schedule     a matrix that maps people to shifts
%   schedules(n).index       an array of people who are working this sched
%   schedules(n).grid        a conversion of "schedule" to a like format
%   schedules(n).numpeeps     how many people were required for the sched
%   schedules(n).numdays      Schedule rotation score
%   schedules(n).numsets      the number of possible assigned shift sets
%   schedules(n).score       efficiency rating of each schedule
%   schedules(n).ratio       Flexibiltiy Ratio (FR = S/O)
%   schedules(n).person(k).number       unique number for each person
%   schedules(n).person(k).consecutive  consecutive days for each person
%   schedules(n).person(k).shift        time of day worked by each person
%   schedules(n).person(k).days         array of shift assignments
```

```
%Initialize all random schedules
for n=1:numsched
   schedules(n).schedule = zeros(3,numdays);
end

%each n corresponds to a unique schedule solution
for n=1:numsched
   schedules(n).holes = shifts;
   holes = sum(sum(schedules(n).holes));
         %each k corresponds to a unique employee
   k=1;

%Run while loop as long as any values in holes matrix are zero

while holes < 3*numdays

   %initialize consecutivity check matrix to zeros
   schedules(n).person(k).consecutive = zeros(1,numdays);

   %initialize shift assignments to zeros
   schedules(n).person(k).days = shifts;

   %Assign a number to each employee in the structure
   schedules(n).person(k).number = k;

         %Set what shift each person is working each day
   schedules(n).person(k).shift = 0;

         %No previous schedules to compare to so create unique schedule. Often this means k1 works all
         shift 1, k2 works all shift 2, and k3 works all shift 3, depending on values of numdays and maxdays
         used

   if k == 1
      %for each new schedule, start first person on nth day
      index=n;
   else
      %second and later people start on random day
      index=randi(numdays);
   end


   for i=index:numdays

   %Starting from random index, each person fills in the schedule

   for j=1:3
      if i == 1 && schedules(n).holes(j,i) == 0 && schedules(n).person(k).days(1,i) == 0 &&
schedules(n).person(k).days(2,i) == 0 && schedules(n).person(k).days(3,i) == 0
         schedules(n).person(k).days(j,i) = 1;
         schedules(n).person(k).shift = j;
```

```
        schedules(n).holes(j,i) = 1;
        schedules(n).schedule(j,i) = k;
      elseif i > 1 && (schedules(n).person(k).shift == 0 | schedules(n).person(k).shift == j) &&
schedules(n).holes(j,i) == 0 && schedules(n).person(k).days(1,i) == 0 && schedules(n).person(k).days(2,i) ==
0 && schedules(n).person(k).days(3,i) == 0 && schedules(n).person(k).consecutive(i-1) < maxdays
        schedules(n).person(k).days(j,i) = 1;
        schedules(n).person(k).shift = j;
        schedules(n).holes(j,i) = 1;
        schedules(n).schedule(j,i) = k;
      end
  end


  %Increase consecutivity counter
  for z = 1:numdays
  if z == 1
      schedules(n).person(k).consecutive(i) =
schedules(n).person(k).days(1,z)+schedules(n).person(k).days(2,i)+schedules(n).person(k).days(3,z);
  elseif schedules(n).person(k).days(1,z) == 1 || schedules(n).person(k).days(2,z) == 1 ||
schedules(n).person(k).days(3,z) == 1
      schedules(n).person(k).consecutive(z) = schedules(n).person(k).consecutive(z-1)+1;
  end
  end

  end

  %Sum total holes remaining for next run of loop
  holes = sum(sum(schedules(n).holes));

  %Step to next person index
  k=k+1;
end


%Convert the grid created in schedules.schedule into schedules.grid to avoid repeat schedules. For
example, [2 2 2 3] is the same as [10 10 10 5]; both convert to [1 1 1 2]

schedules(n).index = zeros(1,max(max(schedules(n).schedule)));
schedules(n).grid = zeros(3,numdays);

z = 1;

while z < max(schedules(n).schedule)
  for j=1:3
      for i=1:numdays
        if ismember(schedules(n).schedule(j,i),schedules(n).index) == 0
          schedules(n).index(z) = schedules(n).schedule(j,i);
          schedules(n).grid(j,i) = z;
          z = z+1;
        else
```

```
            for a=1:max(schedules(n).schedule)
               if schedules(n).schedule(j,i) == schedules(n).index(a)
                  schedules(n).grid(j,i) = a;
               end
            end
         end
      end
   end
end

%Calculate how many people needed for the schedule (J)
schedules(n).numpeeps = max(max(schedules(n).grid));

%Calculate number of shift blocks in the rotation (S)
schedules(n).numsets = schedules(n).numpeeps*numweeks;

%Calculate FR = S/O
schedules(n).ratio = schedules(n).numsets/certs;

%Calculate the schedule rotation cost

schedules(n).numdays = zeros(1,numdays);
schedules(n).score = zeros(1,numdays);

%Loop for calculating rotation score. Index d allows for separate score for starting on each day of the week,
which affects the weekend scoring.

for d = 1:numdays

%Create a matrix "grids" for each person in the schedule
for z = 1:schedules(n).numpeeps
   %c is a temporary consecutivity counter
   %t is a temporary total days counter
   c = 0;
   t = 0;
   nights = 0;
   grids = zeros(3,numdays);

   grids = schedules(n).grid;

   for j = 1:3
      for i = 1:numdays
         if grids(j,i) ~= z
            grids(j,i) = 0;
         elseif grids(j,i) == z
            grids(j,i) = 1;
         end
      end
   end
```

```
%Calculate the schedule rotation cost

%Add 1 for each person working entire weekend
   if d ~= 7 && (grids(1,d) == 1 | grids(2,d) == 1 | grids(3,d) == 1) && (grids(1,d+1) == 1 | grids(2,d+1) == 1 |
grids(3,d+1) == 1)
      schedules(n).numdays(d) = schedules(n).numdays(d)+1;
   end

%Add 2 for each person working nights

   nights = sum(grids(1,:));

   if nights >= 1
      schedules(n).numdays(d) = schedules(n).numdays(d)+2;
   end

%Add 1 for each person working swing shift

   evens = sum(grids(3,:));

   if evens >= 1
      schedules(n).numdays(d) = schedules(n).numdays(d)+1;
   end
end

%Calculate final score for each schedule:
%Score = PR*FQ
%Where PR =(maxscore-cost)/maxscore and FQ = 1-1/(10*FR)
schedules(n).score(d) = (maxscore-schedules(n).numdays(d)-
schedules(n).numpeeps*switchfactor)/maxscore*(1-1/(10*schedules(n).ratio));

end
end
```

Script call for function

```
schedule_creator_final(7,7,13,500,0.5,30)

%This is a script to call the function schedule_creator_final. It provides inputs to the function and indexes
results using "sort". The script then plots the results to assist with analysis

%Ensure that the resulting data is stored somewhere other than "ans"
schedules = ans;

%Sort scores highest to lowest
[M1,I1] = sort([schedules.score],'descend');
```

```
%Sort number people (J) highest to lowest
[M3,I3] = sort([schedules.numpeeps],'descend');

%Sort Flexibility Ratio highest to lowest
[M4,I4] = sort([schedules.ratio],'descend');

%For loop needed due to 7*numsched number of scores to sort
%The x variable in this loop finds the schedule number for each score
%which allows for comparison of FR to J in the plot.
for n = 1:3500
   x = ceil(I1(n)/7);
   y = schedules(x).ratio;
   z =schedules(x).numpeeps;
   N1(n) = y;
   N2(n) = z;
end

%Plot scores versus FR
yyaxis left
plot(M1)
yyaxis right
plot(N1)

figure

%Plot scores versus J
yyaxis left
plot(M1)
yyaxis right
plot(N2)
```