DESIGN OF A SINGLE PILOT COCKPIT FOR AIRLINE OPERATIONS

PROJECT REPORT

AUTHORED BY
Jonathan Graham
Christopher Hopkins
Andrew Loeber
Soham Trivedi

SPONSORED BY
Mr. Andrew Lacher of the Center for Advanced Aviation System Development MITRE
Dr. Lance Sherry of the Center for Aviation Systems Research GMU

George Mason University
Department of Systems Engineering & Operations Research
4400 University Drive
Fairfax, Virginia 22030

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1.0 Context Analysis

Commercial air transportation is an immensely complex system and an equally complex business. Transportation is a large percentage of the US economy with commercial aviation accounting for 4.9% – 5.2% of total US GDP [1]. Moving cargo and passengers around the world is a vital service with far reaching impact to consumers and businesses. Successfully operating such a complex system is dependent on a business’ ability to efficiently meet transportation demand by balancing operating constraints and financial goals. As major stewards of economic growth, commercial aviation is responsible for balancing flight demand with profitability driving business decisions.

Despite air transportation’s importance, the industry has historically had extremely poor financial performance over the course of its existence, which has intensified in recent years. Between 2000 and 2012 thirty percent of all United States based airline companies have filed for chapter eleven bankruptcy.

Figure 1: Profit/Loss and Net Income for commercial air carriers. Overlayed are bankruptcy filling events. Note: values are adjusted for inflation to 2012 dollars.

Figure 1 illustrates the volatile nature of the industries finances in the last two decades. The chart specifically demonstrates the financial performance of major US based air carriers, which, for the purposes of this study, will be defined as any agency with operating revenue greater than twenty million dollars. A portion of this volatility can be correlated with major market trends at the time, such as the dotcom bubble of March 2000, which acted as a
catalyst in exposing some of the underlying issues plaguing the industry. The crash in 2000 ended the period of relative financial stability that had lasted through most of the previous decade.

The major contributor to the industry’s poor financial performance has been rampantly increasing operating expenses. As shown in Figure 2, total operating expenses have grown steadily over the last two decades with several noticeable spikes during the last decade. Based on data taken from the Bureau of Transportation Statistics (BTS) the total operating expenses are expected to grow by approximately three billion dollars annually.

![Projected Total Operating Expense for Major Air Carriers](image)

*Figure 2: Yearly operating expense for large US air carriers domestic operations with projected expense based on exponential fit. Note: adjusted for inflation to 2012 dollars.*

Furthermore, Figure 3 shows that revenue has not consistently been above expenses indicating a lack of consistent profitability. There is a need to push operating expenses significantly below revenue in order to create a stable financial system.
Eighty percent of total operating expenses can be decomposed into four major categories: fuel costs, airline operations, pilot labor costs, and direct maintenance costs. As illustrated by Figure 4 airline operations, pilot labor, and direct maintenance costs have all remained relatively static over the past two decades. Fuel costs, however, have rapidly risen since the end of the 1990’s. Fuel costs are variable, and dictated by entities outside of the airline industry. Other costs, like pilot labor are within the jurisdiction of airline management and can therefore be manipulated to beneficially affect the industry’s total operating expense. Pilot labor costs make up fewer than six percent of total operating expense. Although pilot labor costs have remained relatively constant over the last two decades it is beginning to slowly increase.
According to the FAA’s *Aerospace Forecast FY 2013-2033* a 3% yearly increase in revenue passenger miles is projected over the period of 2012-2022 [2]. That is equivalent to a 30% increase in passenger demand by the end of the next decade. Using BTS data as the baseline for comparing passenger miles demand with operating expense, it is shown that there is an 26.95% increase in passenger miles (slightly less than FAA forecasts) from 2012-2022 [3]. Since the scope of the analysis is concerned with domestic operations, the total increase in demand for domestic passenger miles is projected to increase 33.28% based on the same BTS data when fitted for domestic passenger miles only. As it is shown in Figure 5, domestic passenger demand comprises the majority of passenger miles flown.

![Projected Passenger Miles](image)

*Figure 5: Total and domestic passenger miles based on a regression fit of R^2=0.86 and R^2=0.78 respectively.*

Rising expenses and declining revenues have motivated airlines to operate aircraft that have reduced crew requirements enabled by technological innovations. With advances in technology, the systems benefit with increased reliability, safety, and affordability [4]. Fundamentally, the dynamics of aircraft flight haven’t changed but advancements in flight control technologies, imposed by the need to reign in operating expenses, have significantly shaped the way systems operate, or more appropriately, how pilots fly the aircraft.

A core component in any aircraft and air transportation system are the pilots who fly the aircraft. As the need for reduced operating expense has lead to advanced technologies in the aircraft, the roles and functional need of pilots change. The goal of this
The project is to design a system that supports a level of automation that would enable the flight of an aircraft by one pilot to support decreased operating expense while maintaining or increasing system safety and reliability.

1.1 Historical Perspective

Removing pilots from the cockpit has been a strategy used in the past to help save on labor costs, as aircraft that require fewer pilots decrease the cost associated with flying the aircraft. Originally, a cockpit contained five pilots, each filling a distinct role. Over time, the roles of navigators, flight engineers, and radio operators have been eliminated due to technological innovations in their respective functional areas [5]. With the current need for increased financial stability and a solution for the looming pilot shortage, moving from the current two-pilot paradigm to a single pilot cockpit may be the next logical step.

1.2 The Two-Pilot Cockpit

In most major aircrafts there are two pilot roles filled by the captain and co-pilot: they are the pilot flying (PF) and the pilot not flying (PNF). Both the captain and co-pilot can fill either role as needed and often switch to fulfill training/certification requirements. The major responsibilities of the PF include flying the aircraft, confirming callouts and inspecting instruments. The PNF handles of interactions with ATC, performs cockpit callouts, inspects and manipulates instruments and, if needed, takes over the responsibility of flying the aircraft. All of their responsibilities are described within an official FAA approved document called the Flight Crew Operating Manual (FCOM). An FCOM details flight procedures for all potential situations that a plane may be in for both on the ground and in the air operations. For the purposes of this project the team has analyzed the procedures described within the FCOM for a Swiss Airlines owned and operated RJ100 aircraft.

Flight procedures detail the established processes followed to operate an aircraft and the responsible pilot. A procedure is decomposed into a series of tasks within the FCOM. An example procedure is illustrated in the sequence diagram below Figure 6. The procedure shown is one that is completed when a wind shear has been detected. The four standard actors within this procedure and a majority of others are the PF, PNF, Aircraft and ATC.
Each message represents a task, in this case the PF completes a series of physical tasks before performing a cockpit callout at which point the PNF takes over several physical and cognitive tasks before interacting with the ATC.

Figure 6: Sequence diagram for a "Windshear Detection Procedure" out of the RJ100 FCOM

2.0 Stakeholder Analysis

Commercial aviation is a major provider of transportation services. Since aviation is a large part of the US economy, major advancements in the forms of new systems have a large impact for all persons regardless of personal air transportation utilization. The commercial aviation industry has a diverse range of stakeholders involved in its continued operation, each with its own motives, resources, and functions. The various involved parties and the relationships that they have with one another are detailed in Figure 8 and Table 1 below. The involved entities can be divided into four main categories: regulatory agencies (FAA, DoT), aviation workforce (pilots, air traffic controllers, and the unions representing them), aviation infrastructure (airports, aircraft manufacturers, and insurance agencies), and the customer base. While airline companies have a vested interest in increasing their profitability by implementing a single pilot cockpit solution, many of the other agencies in the industry may have serious reservations about moving away from the existing two-pilot system, especially regulatory agencies.
2.1 Commercial Air Carriers

Commercial air carriers are primarily driven by their business objectives. Airline managers are entrusted to operate and monitor the business in accordance with their predefined business objectives. Just like any other business, air carriers must make decisions around how profitability and costs are affected.

Implementing a single pilot cockpit to reduce the need for pilot labor will be a favorable option for commercial air carriers due to the potential cost savings. However, they would run into serious conflicts with many of the aviation industry’s stakeholders, presenting a series of potential challenges in moving forward with implementation. In any market, ignoring the needs of consumers is bad for profitability. Commercial aviation would not survive if it ignored customers, employees, or regulators.
2.2 FAA

As a regulatory body, the FAA’s primary objective is to create and enact policy with the express purpose of maintaining or improving aviation safety. The agency is granted the power to regulate aviation and create policy in line with its mission to create a safe and efficient airspace [6]. As such, the FAA holds the reins on whether or not a single pilot cockpit system would be approved and allowed to operate. The agency would be very skeptical of a single pilot cockpit because it represents such a significant departure from current aviation systems. A single pilot cockpit is inherently counter to the FAA’s objectives because it lowers aircraft reliability by reducing a human pilot by a machine.

Action to resolve conflicts between air carriers and the FAA would be very laborious and time consuming. Rigorous testing and analysis would have to be completed to demonstrate to the FAA that the single pilot cockpit is feasible from a safety and reliability standpoint, as well as prove that the established minimum reliability standards will be met. System design alternatives will have to meet regulatory standards and include long term impact to pilot certification, air traffic control, aircraft certification, and airports. The FAA would be the authority on any impact to the National Airspace System (NAS) in addition to its regulatory role. Objectives may greatly vary from each segment of the NAS. Even if all other stakeholders are brought into agreement on a particular single pilot system, the FAA will be the ultimate hurdle for aviation companies to overcome, as they are required to give the legal authorization to operate such a system.

2.3 Customer Base

The customer base for commercial aviation are mostly concerned about getting from point A to point B as cheaply, comfortably, safely, and timely as possible. They may be concerned about both cost and safety and may be skeptical of flying on aircraft with only one pilot, when they have become so accustomed to flying on planes with two or more pilots onboard. Over time, the fact that one pilot is flying would become less controversial just like any other instance of technology replacing pilots (navigator, radio operator, and engineer). Passengers may take longer to become accustomed to the single pilot system due to the perceived lack of failover capability, such as the fear that the one pilot in the
cockpit may become incapacitated without a co-pilot to provide backup would cause a major aircraft accident. Air carriers can also counteract passengers’ initial safety concerns about single pilot air transport by offering reduced rates compared to their competitors, which would be easier to accomplish with the resultant cost savings following from labor cost reduction.

2.4 Aviation Workforce

The aviation workforce is comprised of pilots, air traffic controllers, and the unions that represent them. They are primarily interested in preserving existing job and wage stability, as well as ensuring that current levels of workload and safety conditions are maintained. The notion that only a single pilot would be needed for air carrier operations would be a serious point of contention between air carriers and pilots. Pilots and unions alike would be extremely worried that a reduction in pilot labor demand from moving to a single pilot system would immediately put thousands of pilots out of work, likely leading them to applying a lot of pushback against the efforts of air carriers to implement such a system.

Air Traffic Controllers (ATC) has immense responsibility to ensure the National Airspace System is safe and well managed. ATC’s objectives are much like the pilot’s in that they want to maintain employment, bring home a stable salary, maintain workload, work in a safe environment, and have career growth opportunities. Air traffic controllers will also likely oppose a single pilot system initially, but for slightly different reasons than pilots. ATC will be primarily concerned that their operational procedures would significantly change under a new system. In addition to changing their procedures, increasing ATC task load would be unacceptable from their standpoint. Systems that seamlessly integrate existing procedures and ATC protocol may be acceptable, though some initial skepticism is expected.
2.6 Aviation Infrastructure

Aviation infrastructure includes aviation insurance companies, airports, and aircraft manufacturers. In general, these agencies are primarily driven by maintaining consistent revenue, market predictability, and a low risk profile, as well as holding onto and expanding on their current customer base.

Aircraft manufacturers have a vested interest in selling and leasing their airplanes to airlines. They are constantly seeking new ways to better their product lineups and take them to market. The move to a single pilot cockpit could prove to be a good opportunity to develop a new, unique product that can be sold or leased for an increased profit compared to older models. As long as the R&D costs involved in redesigning the firm’s existing plane models doesn’t outstrip the potential for a higher profitability, aircraft manufactures would likely be the only stakeholder besides the airlines themselves to push for implementing a single pilot system.

Aviation insurance companies will be keenly aware of the increased level of risk that introducing a single pilot system would have on flight safety. As such, they will likely require a probationary period for testing a plane newly-developed to operate under the single pilot paradigm in order to collect enough data to make the appropriate adjustments to their premiums. As long as insurance agencies are given enough time to adapt their insurance plans to the shifting aviation landscape, they are not likely to have much of an issue with the move to a single pilot cockpit.

Airports serve as departing and arrival junctions for air transportation. The infrastructure required to meet these needs is very complex and requires significant capital investment. Changes to the system would greatly impact operations and may be a significant bottleneck in terms of system operations. Airport’s objectives are to maintain its infrastructure and keep cost of existing or new systems as low as possible. Airports may develop conflicts with the airline companies because they are balancing operations for all sizes of air carriers, different schedules/capacities, and are pressured to ensure there are no gaps in service. Implementing new systems would be perceived as risky and costly regardless of long run benefits or intent, so airports would need to be assured that the added complexity from implementing a new system would not be significant enough to overcomplicate their business operations.
<table>
<thead>
<tr>
<th>Stakeholder Group</th>
<th>Primary Objectives</th>
<th>Tension with Single Pilot Cockpit</th>
</tr>
</thead>
</table>
| **Regulatory Agencies** (FAA, DoT)        | • **Maximize:**  
  • Flight safety  
  • Consumer protection | A SPC would inherently introduce new risks and decrease overall flight safety, leading regulatory agencies to withhold their approval |
| **Aviation Workforce** (Pilots, Pilots’ Unions, ATC, ATC Unions) | • **Maintain:**  
  • Job Stability  
  • Wage Stability  
  • Safety level  
  • Workload | View SPC as a major potential threat to job stability, leading to a high risk of pushback |
| **Customer Base**                         | • **Minimize:**  
  • Travel time  
  • Flight risk  
  • Ticket expenses | May have reservations about flying in a plane with only one pilot, leading them to avoid flying with an airline that uses a single pilot cockpit |
| **Aviation Industry** (Air Carriers, Management, Manufactures, Insurance, & Airports) | • **Maintain:**  
  • Consistent revenues  
  • Customer base  
  • Market predictability  
  • Low risk profile | Want to increase profitability through sales/service, but don’t want to increase expenses commit to long term investments without noticeable return |

Table 1: Table displaying major objective conflicts between stakeholders

2.7 Stakeholder Win-Win

Given the complicated stakeholder relationship for the single pilot cockpit system, a win-win will not be established by selecting a particular alternative, rather it will be an outcome of a long-term “implementation roadmap” that will give each stakeholder time to evaluate and assimilate to change. Figure 8 shows a notional roadmap for implementing and evaluating the single pilot cockpit system.

![Figure 8: Notional Win-Win single pilot cockpit system implementation roadmap](image)
In the win-win scenario, the design alternative will be integrated into the baseline two pilot cockpit. After several years of evaluation and redesign, the two pilot cockpit will be reduced to the single pilot cockpit. This ensures there is ample time for pilot training, ATC coordination, FAA evaluation, and aviation industry evaluation. A summary of how each major stakeholder group benefits in the win-win scenario is given in Table 2.

<table>
<thead>
<tr>
<th>Organization</th>
<th>Tension to be Mitigated</th>
<th>Benefit to Slow Phase-In</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulatory Agencies</td>
<td>Fear of elevated risk caused by removing a pilot</td>
<td>Allows regulatory agencies to observe the effects of implementing a SPC and collect reliability data without the worry of deploying an uncertain system and dealing with damage control.</td>
</tr>
<tr>
<td>Aviation Workforce</td>
<td>Fear of labor downsizing</td>
<td>The resultant decline in pilot labor demand can be spread out over several decades, meaning that job stability can remain relatively stable, and pilots can adapt to using a new system. A SPC system can also potentially reduce a pilot’s workload.</td>
</tr>
<tr>
<td>Customer Base</td>
<td>Fear of boarding a plane being flown by a single pilot</td>
<td>Fliers with concerns about the safety of a SPC will be allowed more time to acclimate to the new technology. Also, the majority viewpoint will shift due to changing generational attitudes regarding automation in general.</td>
</tr>
<tr>
<td>Aviation Industry</td>
<td>Fear of costs/changes needed to adapt to new system</td>
<td>Airports and aircraft manufacturers will be given additional time to adapt their operations, products, and business plans to the current phase of SPC deployment, keeping them from wasting resources on developing unutilized solutions.</td>
</tr>
</tbody>
</table>

Table 2: Win-Win analysis table

3.0 Problem and Need Statement

Commercial aviation is projected to have increasing operating expense from 2013 to 2022 at an increase of 30% based on an exponential regression fit. Growing operating expenses are presumed to relate to growing demand for air transportation. Figure 5 shows the projected demand in terms of yearly revenue passenger miles. Although passenger transportation is not the only demand data point, it is arguably the largest.
The Federal Aviation Administration (FAA) has predicted a six percent growth in demand for pilots between 2012 and 2022 [2]. Unfortunately, due to factors such as a change in flight hour requirements for co-pilots, increased mandatory rest time, and a decreased retirement age from 65 to 60 there is an increasing gap between forecasted supply and demand. Figure 10 graphically depicts the historic pilot labor force with the projected labor supply and demand. A single pilot cockpit system may help reduce the impact to a projected pilot shortage and bring some stability for future labor supply. The projected shortage of pilots will ultimately cost the airlines in terms of lost flight hours and increasing pilot pay. As the number of available pilots decreases, the cost for pilot labor increases and consequently, increases the overall operating expense. A single pilot cockpit could potentially mitigate the effects of a pilot labor shortage by reducing crew requirements allowing the existing labor pool to be spread more evenly.

Figure 9: Projected yearly operating expense based on a regression fit. Note: values are inflation adjusted to 2012 dollars and expenses through 2022 are in present value.
Increasing demand for air transportation, a projected pilot labor shortage, and rising operating expenses will continue to negatively impact commercial aviation's ability to attain stable financial performance. Commercial aviation needs to implement systems that will reduce operating expense so that operating revenue will be larger than operating expense.

Figure 10: Projected pilot labor growth based on FAA Forecast 2013-2033 pilot growth rate.

Figure 11: Operating revenue to expense ratio from 1990-2012. Assume red dotted line is the profitability target fixed based on historical levels.
The GAP in Figure 11 graphically describes the problem: operating revenue as a ratio to operating expense is smaller or close to one over the past twelve years. Assuming that the ratio is an indicator of profitability, bringing the ratio back to the levels of the 1990’s would produce a financially stable industry. Measures that reduce targeted portions of operating expense, i.e. pilot labor, would have an impact on decreasing the gap. Referring back to Error! Reference source not found., it is shown that operating expense on items like fuel and pilot labor are two significant line items that account for a large portion of yearly operating expenses. If a two pilot cockpit is reduced to a one pilot cockpit via automation, the total operating expense of air carriers can be reduced and increase operating revenue. This reduction would impact commercial aviation’s ability to reduce long term operating expense and attain less extreme deviations in profitability.

4.0 Requirements

Requirements drive the design, simulation, and analysis of the system. The mission requirements represent the high level super system requirements for the design alternatives. The focal point of these requirements is safety and cost. Lower level requirements should have traceability to one or more of these four mission requirements. Traceability ensures there is validity within the requirement document.

| M.1 The single pilot cockpit system shall reduce or maintain the baseline pilot flying procedure working time of 20.87+/-3.7s |
| M.2 The single pilot cockpit system shall meet ARP4761 Level B assurance of 1 failure per million flight hours. |
| M.3 The single pilot cockpit system shall decrease yearly pilot labor operating expense. |
| M.4 The single pilot cockpit system shall have a total aircraft lifecycle savings greater than $100,000. |

Because only high-level mission requirements have been identified, it is recommended that separate acquisition requirement documents (where applicable) should be created to detail lower level design, interface, and assurance requirements. One of the challenges preventing in lower level flow down would be the specific aircraft or system the integration effort would take place in.
5.0 Design Alternatives

System design alternatives are described as a black box system. The nature of the design and analysis relies on the fact these technologies are largely absent within the current scope and context (outside of the baseline case). Although the component technologies are available, the integration of these components specifically for task automation/pilot replacement is unfounded. It is the assumption that the feasibility of such designs is derived from the task hierarchy and task performance associated with each alternative.

![Physical process diagram](image)

**Figure 12: Physical process diagram**

The physical process diagram shown in Figure 12 describes the basic operation of the aircraft based on pilots following standardized operating procedures. Pilots acting as the mechanism meet flight goals by aid of the procedures and aircraft avionics. Aircraft control is commanded through the cockpit until an ultimate flight outcome is achieved. The emphasis on operating procedures is of importance for the analysis component of this paper.

5.1 Two Pilot Cockpit

The baseline cockpit system shall be the two pilot cockpits. The majority of aircraft used for air transport require, at a minimum, two pilots to fly. Some aircraft may have requirements for larger crew sizes, but the scope of this analysis is domestic operations;
which presumably eliminates aircraft that may require more than two crew because of aircraft size or flight time.

The RJ100 FCOM will be used as the baseline procedural model for the two pilot cockpits. These procedures will be manipulated per the technological capabilities of each subsequent alternative.

5.2 Single Pilot No Support

Evaluating a system where only a single pilot flies the aircraft with no support for the pilot not flying roles is necessary to see what the change in workload will be for a pilot with and without some sort of technology to replace the flying and support role of the pilot not flying. Procedures where the pilot interacts with the co-pilot will be dropped, but some of the actions performed by the pilot not flying will be transitioned to the pilot flying. Potentially, the component tasks of the procedures maybe reduced. Costs would certainly be reduced by simply transitioning to the single unsupported pilot, though the load from the procedures will more than likely be unsuitable relative to the baseline case.

5.3 Onboard Procedure Support System

Noting that the technology does not exist currently, a “black box” system will be designed to implement automation that handles the task load of a co-pilot. This system design alternative takes flight state data and input from ground based entities and the single pilot. The data is used to execute predefined tasks such as those designated in a flight crew operating manual (FCOM). Automated tasks will fill the void left by the absence of a co-pilot. Feasibility for the task automation system is evaluated in terms of task load on the pilot flying and total lifecycle cost. If safety is impacted i.e. increased pilot task load or full lifecycle cost is too high, the system won’t be a viable alternative. Error! Reference source not found. shows the functional flow of the task automation system.
6.0 Simulation Methodology

The design alternatives provide a mechanism to augment the pilot role being replaced for the single pilot cockpit system. Three important factors are analyzed: how the procedures change relative to the baseline two pilot case, how does the cockpit reliability change, and how does each alternative impact airline operating expense. The roadmap for analysis conducted is shown in Figure 13. Three separate analyses are conducted whose outputs are used for a cost-utility analysis and support recommendations.

![Figure 13: Analysis diagram](image)

Each model and simulation is explained in detail throughout the following section. Results that were collected from each model are placed in the section 7.0 Results. Recommendations are made based on a attribute hierarchy, the requirement satisfaction outcome, and problem/need satisfaction.
6.1 Procedure Model

Procedure models offer insight into how users operate a system. In a cockpit scenario, procedure models can help isolate pilot performance bottlenecks and sources of error [8]. Analysis of flight crew operating procedures is done to create a baseline two-pilot performance for comparing design alternative’s performance. Procedure performance is assumed to be directly related to safety and reliability for the purpose of determining design feasibility.

The procedure model represents the standard operating procedure for flying a sophisticated jet aircraft. The procedures are derived from an RJ-100 Flight Crew Operators Manual (FCOM) and modeled to capture the actions required to complete a procedure which is decomposed by tasks and actions. We first extract each procedure specification sections from the manual into an Excel spreadsheet to identify the responsible entities to execute a task. An example snapshot of the spreadsheet is in Figure 14.

![Figure 14: Snapshot of tasks from the RJ100 FCOM.](image)

The tasks are composed of functions that require specific physical and/or mental actions to be performed by one or both pilots. Responsible entities are identified as: Pilot Flying (PF), Pilot Not Flying (PNF), Co-Pilot (COPI), Pilot Occupying the Left Seat (PIC), and Both Pilots (B/P). Each task has one or more identified actions associated with its execution. Actions are described in Table 3. Once codified into the spreadsheet, the model is transformed into an XML schema which serves as the input into the simulation. The XML procedure model increases the number of actions as more fidelity is added to each task in the hierarchy model. The ability to design a full human factors experiment with live pilots as experimental subjects is outside the scope of this systems design and analysis. The simulation was made to facilitate a notional representation of perception, cognition, and motor performance. Given the infancy and lack of validation for the model, we chose to
only model normal operating procedures and ideal entity behavior, i.e. the “perfect” pilot. The procedure simulation section will discuss the underlying human factors model in greater detail, to include experimental design and input modeling.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Instrument Manipulation</td>
<td>Classifies tasks that require an entity interact physically with avionics or controls</td>
<td>• Pushing Throttle Forward</td>
</tr>
<tr>
<td>Verbal Cockpit Callout</td>
<td>Tasks that require specific verbal messages to be broadcasted for all crew to hear</td>
<td>• Announce Checklist is Completed</td>
</tr>
<tr>
<td>Physical Flight Computer Interaction</td>
<td>Extended interaction with the flight computer comprises several defined actions so it is described by its own category</td>
<td>• Inputting Flight Plan</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Accepting New Plan ATC</td>
</tr>
<tr>
<td>Auditory Reception</td>
<td>Tasks requiring directed interaction and listening states fall into this category</td>
<td>• Listening to Radio</td>
</tr>
<tr>
<td>Memory Action</td>
<td>Actions that are to be preformed based on abnormal and emergency scenarios</td>
<td>• Emergency Task</td>
</tr>
<tr>
<td>Visual Instrument Inspection</td>
<td>Observing and checking an instrument has a target value</td>
<td>• Check Warning Light On</td>
</tr>
<tr>
<td>Visual Environment Inspection</td>
<td>Observing the outside of the airplane (flight environment)</td>
<td>• Look Out for Runway on Approach</td>
</tr>
<tr>
<td>Verbal External Communication</td>
<td>Extended periods of conversation requiring specific focus</td>
<td>• ATC Comms</td>
</tr>
</tbody>
</table>

Table 3: Table lists the basic physical and mental actions that are required for each task.

The procedure model is decomposed further into a custom XML schema so that it can later be easily parsed into the simulation program. The base schema is shown in Figure 15. Tasks are decomposed based on the entity responsible and their responsible actions. Each action is accompanied by simulation specific parameters. The parameters allow each model to fix the number of chunks for each action to override chunking performed by random variables (which is described later).

The procedure model is assumed to be authoritative when instantiated for specific flight scenarios, that is, behavior (if any) outside the scope of the FCOM will not be considered. An individual procedure model is created for each design alternative before being input into the simulation program. The procedure model abstracts the capabilities of
each technology in the form of functional performance. The functionality manipulates which component tasks and actions can be handled by a new system replacing a pilot. The remaining pilot in each procedure model will have changes to their procedure based on hypothetical interaction with each design alternative.

```xml
<ProcedureModel>
  <procedure>
    <entity>
      <task>
        <name></name>
        <action></action>
        <VSen></VSen>
        <CE></CE>
        <Hicog></Hicog>
        <PM></PM>
        <BG></BG>
        <Mouth></Mouth>
      </task>
    </entity>
  </procedure>
</ProcedureModel>
```

Figure 15: XML schema used to parse Excel sheet.

An important step in creating each procedure model was the manipulation of procedures specific for each design alternative. A rule of thumb was used to develop each model. The motivation for the changing model is the real world implications of each design. For instance, if a single pilot was flying the aircraft, then there would be an elimination of activities which, in the two pilot baseline case, would involve extended interaction between the pilot and co-pilot. The implications for the single pilot however are the increase workload and effort with a decrease in overall procedure time (due to the decrease in component tasks and actions to complete the procedure). The performance measures for each model are reflected in the procedure simulation, where these expected behaviors (workload increase and time decrease) should be present. The rules for how each model was created are listed in Table 4. As the designs mature and simulations undergo validation, these rules and models would be expected to change.
<table>
<thead>
<tr>
<th>Design Alternative</th>
<th>Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two Pilot Cockpit</td>
<td>No changes made to procedures; represents baseline procedures as defined in the flight crew operating manual.</td>
</tr>
<tr>
<td>Single Pilot with No Additional Support</td>
<td>Pilot Not Flying tasks transferred to Pilot Flying.</td>
</tr>
<tr>
<td></td>
<td>Verbal cockpit callouts removed</td>
</tr>
<tr>
<td></td>
<td>Duplicative confirmation tasks removed</td>
</tr>
<tr>
<td>Single Pilot with Procedure Support</td>
<td>Avionics takes on confirmation checks as output to a display</td>
</tr>
<tr>
<td></td>
<td>Verbal cockpit callouts eliminated</td>
</tr>
<tr>
<td></td>
<td>Tasks added to accommodate avionics triggering mechanism</td>
</tr>
</tbody>
</table>

Table 4: Rules for changing the FCOM for each alternative

6.1.1 Procedure Simulation

The procedure simulation is used to analyze the predicted performance and risk of system alternatives under a series of normal flight conditions. These procedures are created to gather evidence for operational feasibility, reliability, and safety. The simulation parses the procedure model for each design alternative and executes tasks based each model. The simulation outputs the results of execution times and workload for each task and entity to produce an overall procedure execution time for each alternative’s procedure model.

The simulation is coded in Java with several additional libraries to enhance random variate generation and statistical analysis. The program begins by loading the procedure model and parsing the XML structure into different classes. The task structure is preserved through the class structure. In this way, several procedure models can be loaded and ran in the same replication. Procedures are executed through the iteration of each entity, task, and action in a sequential fashion. Statistics are gathered for each run of the procedure simulation.
The complex nature of flying operations leads the simulation to operate based on several assumptions. The following is the lists of assumptions used in the simulation.

1. Human Processor Model approximate operator actions in cockpit under normal flight conditions
2. Events are independent of each other
3. Normal flight conditions and expert skill level
4. Assume alternatives follow contemporary avionics costs
5. RJ100 FCOM is representative of similar operating manuals compiled by commercial airlines
6. Assume procedures in operating manual are complete representation of flight
7. Additional company specific pilot tasks not included

Based on the assumptions above, the model human processor is used to process actions from the procedure models in a queuing network. Table 5 shows the processing times for each node in the network which acts according to each human process, i.e. perception, cognition, and motor [8]. The simulation iterates through the tree and replicates the simulation results in a Monte Carlo simulation fashion governed by the equations in Figure 16.

<table>
<thead>
<tr>
<th>Name</th>
<th>Time</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes</td>
<td>50ms</td>
<td></td>
</tr>
<tr>
<td>VSen</td>
<td>N(263ms,10ms)</td>
<td>Perception</td>
</tr>
<tr>
<td>Ears</td>
<td>10ms</td>
<td></td>
</tr>
<tr>
<td>ASen</td>
<td>50ms</td>
<td></td>
</tr>
<tr>
<td>CE</td>
<td>Exp(70ms)</td>
<td>Cognition</td>
</tr>
<tr>
<td>SMA</td>
<td>180ms</td>
<td></td>
</tr>
<tr>
<td>M1</td>
<td>70ms</td>
<td></td>
</tr>
<tr>
<td>PM</td>
<td>A+Bexp(-aN)</td>
<td></td>
</tr>
<tr>
<td>BG</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The alternative processing time is an expected value generated from several replications of the simulation for a target confidence interval. The processing time is the summation of the procedures as defined by each alternative’s unique procedure model. Statistical tests are used to determine if there is a significant difference in the expected alternative processing time relative to the two pilot cockpit baseline system design.

Workload is calculated in addition to the processing times. The workload of the single pilot in each alternative is taken as a ratio of average procedure processing time (for each discrete procedure) and the two pilot-pilot flying processing time (again for each discrete procedure). A ratio larger than one shows that for some discrete procedure, the pilot experienced an increase in workload. The design of experiment in 6.1.2 Procedure Simulation Design of Experiment details the inputs and outputs of the simulation.

<table>
<thead>
<tr>
<th>Mouth</th>
<th>10ms</th>
<th>Motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hands</td>
<td>$k\log(D/S+0.5)$</td>
<td>Design Specific Processing Penalty</td>
</tr>
</tbody>
</table>

**Table 5: Processing table for perception, cognition, and motor [8]**

![Table 5: Processing table for perception, cognition, and motor [8]](image)

\[
APT = \sum_{i=1}^{j} \sum_{k=1}^{1} \sum_{m=1}^{n} (\text{Perception} + \text{Cognition} + \text{Motor})_{jn}
\]

\[
AP = \text{alternative processing time}
\]

\[
\text{Task} = k, \text{ Procedure} = i, \text{ Action} = m...n
\]

<table>
<thead>
<tr>
<th>Replications</th>
<th>Analysis</th>
</tr>
</thead>
</table>
| \[
\text{Replications} \ge \frac{(Z_{\alpha/2} + S_{\alpha})^2}{\varepsilon}
\]| \[
\text{Workload, time required} = \frac{\text{Alternative Procedure, time available}}{\text{Two Pilot Procedure}}
\]
| \[
H_0: \text{APT}_{\text{alternative}} = \text{APT}_{\text{control}}
\]| \[
H_1: \text{APT}_{\text{alternative}} > \text{APT}_{\text{control}}
\]
| reject if $p < 0.05$ |


**Figure 16: Equations for the procedure simulation**
6.1.2 Procedure Simulation Design of Experiment

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Procedures &amp; Tasks</th>
<th>Additional Processing Node</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Pilot No Support</td>
<td>$P_1...P_n$ $T_{1m}...T_{nm}$</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two Pilot</td>
<td>$P_1...P_n$ $T_{1o}...T_{no}$</td>
<td>None</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Pilot With Onboard Support System</td>
<td>$P_1...P_n$ $T_{1p}...T_{np}$</td>
<td>$\text{Exp}(1/X)$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6: Procedure simulation design of experiment

6.2 Business Case

The business model aims to determine the cost-savings feasibility of each design alternative. Based on a set of input assumptions, how do the operating costs of major air carriers respond to the decrease of pilot labor? To answer this question, a business case is developed to evaluate each design alternative against. If the expected lifecycle cost is less than the two pilot baseline case, then the design may be evaluated as a suitable system depending on factors such as significance and sensitivity to change. Any savings from removing a pilot from the cockpit will be presumably available for investment into alternative support systems for the single pilot or allocated elsewhere by the airline company as it sees fit.

The lifecycle model is based on the operating cost of the most popular commercial jet airliner – the Boeing 737-300 [9]. Cost parameters are derived from DOT Form 41 reporting specifically for the Boeing 737-300 from 1990-2012 [9]. An acquisition cost of $300 million dollars is used with a salvage value of 25% original cost for the lifecycle model. The lifecycle period is modeled for 25 years based on a markup from the average fleet age in Form 41 reporting.
The above equation is used to generate the lifecycle cost and savings for a period of 25 years (given by $t$). An escalation rate is used for pilot labor as a sensitivity term under the assumption a pilot shortage could cause an increase in labor costs. The discount rate is treated as a sensitivity term as well to give a “best case” or “worst case” costing scenario for an airline company. The bounds of savings between the cases would be the feasible savings or investment capital into a new design on a per aircraft basis. The design of experiment for the business case is shown in: 6.2.1 Business Case Design of Experiment. The varying inputs for sensitivity purposes are shown and covered in depth in the results section 7.0 Results.

\[
ALC = C_{\text{Aircraft}} + C_{\text{Alt}} + C_{\text{Pilot}} \sum_{t=1}^{N} \frac{(1 + e)^t}{(1 + d)^t} + \sum_{t=1}^{N} \frac{C_{\text{Maintenance}}}{(1 + d)^t} - \sum_{t=1}^{N} \frac{C_{\text{Residual}}}{(1 + d)^t}
\]

$C_{\text{Alt}} = \text{alternative unit cost, } C_{\text{Pilot}} = \text{pilot labor cost,}$

$C_{\text{Aircraft}} = \text{new aircraft cost, } C_{\text{Maintenance}} = \text{maintenance costs}$

$C_{\text{Residual}} = \text{salvage value, } e = \text{escalation rate, } d = \text{discount rate}$

$t = \text{time (years)}$

\[
\text{Net Savings} = \sum_{t=1}^{N} \frac{S_t}{(1 + d)^t} - \sum_{t=1}^{N} \frac{\Delta I_t}{(1 + d)^t}
\]

$S_t = \text{Savings in year } t, \Delta I_t = \text{Additional investment, } d = \text{discount rate}$

$t = \text{time (years)}$
6.2.1 Business Case Design of Experiment

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Alternative Cost</th>
<th>Pilot Cost</th>
<th>Maintenance Cost</th>
<th>Residual Cost</th>
<th>Interest</th>
<th>Lifecycle Cost</th>
<th>Net Saving</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single Pilot No Support</td>
<td>$0</td>
<td>$141,927</td>
<td>$9.127M</td>
<td>$8M-$9M</td>
<td>d=1%-10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two Pilot</td>
<td>$0</td>
<td>$269,126</td>
<td>$9.127M</td>
<td>$8M-$9M</td>
<td>d=1%-10%</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single Pilot With Onboard Support System</td>
<td>($100K,$4.38 M)</td>
<td>$141,927</td>
<td>$9.127M</td>
<td>$8M-$9M</td>
<td>d=1%-10%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 7: Design of experiment for the business model*

6.3 Reliability Modeling

Reliability implications removing a pilot from the cockpit are critical elements in the system design. Starting with reliability block diagrams at the highest level, feasibility of alternatives are determined when compared to current baseline flight safety of US airlines in US national airspace.

According to the NTSB, an average of 2.2 major accidents occurred yearly from 1993-2012 where major accidents are categorized by loss of life or catastrophic loss of aircraft hull [10]. The average yearly flight time over that same period was 17.08 million hours [10]. Treating the major accidents as a failure in the system, a failure rate was calculated using $\lambda = \frac{\sum \text{accidents}}{\sum \text{flight time}}$. The system failure rate (denoted $\lambda_S$) was calculated to be $1.288^{-7}$ accidents per hour. Using this failure rate, a reliability requirement for any arbitrary point in time can be established. The reliability at 1 million flight hours is used for this analysis. Using the aforementioned data, the scoped US airspace system reliability at 1 million flight hours is 0.8674.
For the three different design alternatives, reliability block diagrams were created to model how cockpit and aircraft reliability interact to form the overall system reliability ($R_s$). In each configuration, the behavior of serial and parallel components are followed by the respective exponentially distributed equations $R_s(t, R_{1,n}) = \prod_{i=1}^{n} R_i = \exp\left(\frac{-t}{\sum_{i=1}^{n} R_i}\right)$ and $R_s(t, R_{1,n}) = 1 - \prod_{i=1}^{n} (1 - R_i)$ where any discrete component reliability is given by $R_i = \exp(-\lambda t) = \exp\left(-\frac{t}{MTBF}\right)$.

The RBD in Figure 17 models the two pilot baseline case. In this configuration, a pilot incapacitation event would have minimal impact to the overall system reliability because the remaining pilot will have full flight capability, assuming there are not other failures in the remaining components.

The RBD in Figure 18 represents a single pilot in the cockpit. Under this configuration, any incapacitation to the pilot flying would cause a catastrophic failure to the system. To maintain baseline safety, the reliability of each pilot operating in the US airspace would have to achieve a significantly small failure rate – a critical piece of information for the ultimate recommendation.
The final block diagram in Figure 19 models the single pilot with an onboard support system. An important assumption is made for the onboard support system. For this analysis, we assume that there is ability for auto-landing or recovery in the event of a pilot incapacitation. This assumption seems reasonable given the maturity of existing UAS technologies in use by the military and the emerging civil market. Further analysis would be needed upon deeper design but at this stage, the functionality will be granted essentially creating a surrogate co-pilot as in Figure 17.


7.0 Results

After running simulations and building the models, outputs were analyzed to see if there was any evidence that could support design recommendations. Utility-cost analysis is performed to rank alternatives and make recommendations. In addition to the ranked alternatives from our analysis, further recommendations for expanding the research are made.

7.1 Procedure Simulation Results

The procedure simulation described in 6.1.1 Procedure Simulation was ran for 1000 replications for each procedure model for a total of 3000 total replications. An output set was created for each model so independent statistics could be collected for each population, i.e. each simulation dependent on a procedure model. A sample of procedure times was collected for each alternative as shown in Figure 20. From a heuristic standpoint, the output shows the two pilot baseline required more time to complete procedures. This follows the expected behavior because presumably two pilots perform more cross checks and extended interactive tasks than the other two single pilot designs.

![Sample Average Procedure Times](image)

*Figure 20: Sample average procedure times*

The onboard procedure support system with the single pilot is sometimes faster than the other alternatives due to machine processing time being faster than the human processing
time. Efficiencies in procedure design and functionality could be extended to maximize the human-computer interaction beyond the simplified black box approach taken in this research. The single pilot doesn’t have as many tasks to complete their procedure so only a single entity is handling the cockpit interaction. At the same time though, only one person can complete flight procedures which may impact workload which is described in greater detail later. Using statistical hypothesis testing (parametric and non-parametric), the single pilot and single pilot with onboard support had smaller procedure processing times than the baseline two pilot cockpit $p < 0.0001$

**Procedure Processing Time Distributions**

![Histogram of procedure times from 1000 replications](image)

Another important step in analysis of the procedure simulation was testing if the outputs followed a particular statistical distribution. There wasn’t enough statistical evidence to suggest the simulation followed a known distribution using a Chi Squared hypothesis test for Normal, Exponential, Lognormal, Gamma, and Weibull distributions.

Workload was determined in the simulation by using the ratio of alternative pilot flying procedure processing time to baseline pilot flying procedure processing time for each ith discrete procedure $workload_i = \frac{t_{\text{Alternative PF}}}{t_{\text{Baseline PF}}}$.
Figure 22: Workload plot

The workload for the single pilot was found to be significantly higher than the baseline two pilot case. The result matches expectations where the single pilot may have reduced procedure processing time, but is the only one performing procedures. Another way of stating it is: the single pilot works harder but doesn’t spend as much time flying. The other alternative (single pilot with onboard support) was shown to marginally decrease workload. In this case, the pilot worked less and spent less time flying. Quantitatively, the single pilot workload was on average 4.17 ± 1.77 and the single pilot with onboard support had a workload of 0.75 ± 0.13 with the single pilot processing time being smallest $p < 0.0001$ and the single pilot having greater workload than the single pilot with onboard support $p < 0.0001$

7.2 Reliability Modeling

Using the reliability block diagram models in 6.3 Reliability Modeling and the variation of failure rates in the design of experiment section, a range of reliability (at 1 million flight hours) is given for each design with respect to serial and parallel combinations of components. By fixing aircraft reliability at 0.95 (admittedly lower than real life), we found a range of failure rates that could be combined in the cockpit to reach the baseline air system reliability of 0.8674 (described in great detail in 6.3 Reliability Modeling). The curve generated in Figure 23 shows the feasibility region for a generic component (pilot-pilot or pilot-onboard system).
One of the important findings for the single pilot cockpit was that to achieve baseline flight safety, the entire system would have to have pilot failure greater than $\lambda = 10^{-23}$ failures per hour, a significant increase from the current system. Because of the low failure requirement, the single pilot with no support is deemed to be infeasible and doesn’t meet safety requirements.

The single pilot with onboard support would follow the feasibility region shown in Figure 23 because it has assumed failover redundancy with the pilot flying. If this functionality is not achievable from a design or cost standpoint, than the alternative would be no different than the single pilot with no support and therefore fail to meet safety requirements. Again, it is the judgment of this research that such capability could be integrated and achieved by an onboard piece of avionics hardware (and/or coupled with ground systems).

### 7.3 Business Case

The lifecycle cost model determined lifecycle savings based on two important variables: barrier interest and pilot labor escalation. In the best case scenario, i.e. low barrier and high escalation of costs, the savings was calculated to be $4.38 million over a 25 year aircraft lifetime. Figure 24 shows the range of savings given the combination of
conditions for the model. The cost savings is on a per-aircraft basis so the larger the fleet, the larger the savings. At the pessimistic end of the results, savings were found to be only $100k. Stronger and better tailored lifecycle costing should be done because we assess the feasible savings is very conservative and is likely to change given variable company operating costs and performance.

![Single Pilot Savings](image)

**Figure 24:** Feasible savings region given a barrier and escalation rate

An attribute hierarchy (Figure 25) was developed based on the analysis conducted. Values were converted on a linear scale for each attribute. Using the swing weight method, utility was calculated for each alternative.

![Value hierarchy for recommendations](image)

**Figure 25:** Value hierarchy for recommendations
Before soliciting weights for the hierarchy, a sensitivity analysis was conducted to see if any one alternative dominated regardless of weights on the hierarchy. Using a combination of 0.9, 0.5, 0.5 on each attribute, the following results were determined in Figure 26.

**Utility vs. Cost**

The two pilot cockpit (no change) and the single pilot cockpit with onboard support had the highest utility in all combinations with the single pilot option marginally cheaper than the baseline option. The only category where the single pilot with no support would rank among the other alternatives (and win in cost) would be if procedure processing time reduction was valued the most. Per stakeholder analysis, it is the case that this category would not be valued in such a manner to cause a reduction in time to outweigh reliability and pilot workload (safety factors). From the system need satisfaction criteria, a reduction in cost is needed to help reduce overall operating expense to the airlines.

In addition to the utility vs. cost analysis, the requirement satisfaction was evaluated based on the outputs of the various analyses. Figure 27 shows the satisfaction matrix with respect to each alternative and mission requirement. The single pilot cockpit with onboard support satisfied all mission requirements and is judged to meet the system need.

**Figure 26: Utility vs. Cost plot**
Based on resulting analysis, a series of recommendations are made from the context of improving and expanding the research presented in this paper.

R.1
Recommend the single pilot cockpit with an onboard support system be selected over the two pilot cockpit (no change) option because of cost savings and predicted performance improvements with respect to workload and procedure processing time.

R.2
Recommend the win-win roadmap be utilized for the purpose of iterating the design, integration, testing, and evaluation activities required for the eventual migration to a single pilot cockpit design.

R.3
Recommend the procedure simulation be extended to a live pilot/aircraft dynamic simulator where the human processor model can be validated and calibrated for commercial pilots. The simulation could be used for further design work with respect to requirements development and cockpit human factors research.
**R.4**
Recommend the lifecycle model be tailored for a specific company’s operations and add efficiencies from system designs such as improved fuel consumption and reduced maintenance burden (if applicable).

**R.5**
Recommend a requirements baseline be developed for the single pilot with onboard support system beyond the “black box” approach taken in this research.

Overall, the single pilot cockpit is judged to be a naturally evolved solution to the airline industry’s cost constraints. Further analysis and design is needed to mature the concept beyond high level models, but a body of ongoing research is available to support such activities.

**9.0 Project Management**

**9.1 Work Breakdown Structure**

The work breakdown structure for the projects is comprised of twelve root level tasks which are decomposed further into several subtasks for a total of one hundred and twenty tasks. The WBS serves as the basis for scheduling and cost estimation. Tasks are defined in an iterative and sequential manner rather than intertwining dependencies across each section. The independence of each root level category is designed in such a manner that the WBS is a combination of twelve distinct sub-plans.
9.2 Schedule

Based on the WBS as defined in 9.1 Work Breakdown Structure, the schedule consists of all component subtasks and milestones that make up the overall project. The critical path for the project is through the 10.0 Deliverable Preparation & Assembly tasks. Because so much time is dedicated to preparing for preliminary and final deliverables, the most important part of the overall schedule is described by the work under 10.0 Figure 29 shows the tasks involved in completing WBS 10.0 Though there are not the most concentrated in terms of frequency, they take the most amount of time and resources to complete. It is important to note that the 8.0 Modeling and Simulation task hierarchy is a close second to the established critical path. Most of our risks arise in section 8.0
Figure 29: Representation of WBS tasks with critical path(s) in red
9.3 Budget

The budget to complete the project is based on a $50.00 hourly rate per person with a GMU overhead factor of 47% for a total billing rate of $106.38 per hour. The estimated hours required to complete the project is 701 hours. The planned budgeted value of the project is $74,574.47

9.4 Risk and Mitigation Plan

Risks to the project have been identified with all but one (busy co-sponsor) affecting critical path tasks. Steps have been identified to mitigate the identified project risks.

<table>
<thead>
<tr>
<th>Risk</th>
<th>Description</th>
<th>Mitigation</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation Complexity</td>
<td>There is a chance that the complexity of the simulation and task model will cause scheduling delays which may impact the ability to produce results for the IEEE paper due in February.</td>
<td>Plan to devote significant work to simulation during the winter break period. Simulation coding started ahead of schedule.</td>
<td>Likelihood: Likely Impact: Major</td>
</tr>
<tr>
<td>Procedure Complexity</td>
<td>The number of tasks to be modeled is very large and takes significant resources due to manual nature of input.</td>
<td>Plan to make scope changes to simulation to target a subset of tasks should risk become an issue.</td>
<td>Likelihood: Likely Impact: Major</td>
</tr>
<tr>
<td>Busy Co-Sponsor</td>
<td>NASA Ames researcher has been unavailable to support project.</td>
<td>Working with other sponsors to get additional resources.</td>
<td>Likelihood: Likely Impact: Minor</td>
</tr>
<tr>
<td>Input Data</td>
<td>Serious assumptions were made in regards to task performance modeling. Further information is required to find additional data to validate assumption or provide actual performance data.</td>
<td>Soliciting feedback from professors, sponsor, and professional pilots. Professors will provide insight into stochastic modeling and sponsor/pilots to provide input data.</td>
<td>Likelihood: Very Likely Impact: Major</td>
</tr>
</tbody>
</table>

Table 8: Risk and risk mitigation planning table
9.5 Performance

Earned Value is used to track the performance of the project. We have started over budget due to front-end work on deliverables, but expect to fall below the planned value as milestones are passed. To estimate work completion rate, the ratio of number of subtasks completed to total tasks in a WBS category is used.

![EVM Graph](image)

Figure 30: EVM and Budget

Figure 31 shows the CPI and SPI indexes for the project by week. The schedule and cost increases are shown to reflect the EVM and budget from Figure 30. At the current state of the project, the group is approaching target budget and schedule. A worst case and best case budget have been created to show performance margin. The budgets are created based on ±25% of the planned budget.
Figure 31: CPI and SPI
10.0 References


