

Design of a Single Pilot Cockpit for Airline Operations

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Abstract – Rising fuel and operating expenses for commercial airline operators coupled with a predicted pilot labor shortage drives the need for a reduction in costs while continuing to service passengers. One possible solution to reduce recurring costs and mitigate the effects of a pilot shortage is the transition to a single pilot cockpit. Three different design alternatives for implementing a single pilot cockpit in commercial domestic jetliners were identified: the no change option represented by a two pilot cockpit, a single pilot with no additional support, and a single pilot with an onboard support system that automates some of the removed co-pilot roles. Design alternatives were evaluated using three models: (1) life-cycle cost, (2) reliability, and the (3) processing times for flight procedures based on a human processor simulation. The lifecycle cost model was used to determine the savings generated by a single pilot cockpit. Reliability analysis was done to establish failure rates relative to the target level of safety. A human performance model was developed to evaluate the time on task for each task in the Flight Crew Operating Manual (FCOM) for each alternative. The procedure models were decomposed into component tasks and actions required to complete the procedure. The ranking of alternative designs during utility/cost analysis was found to be (1) the no change option, (2) the single pilot with an onboard support system, and (3) the single pilot with no additional support. We found a tradeoff between the two pilot utility and single pilot with onboard support through cost savings. Based on the analysis of results, the single pilot with an onboard support system was judged to have the best chance for becoming a realistic single pilot cockpit system which will reduce recurring airline operating costs, maintain or improve flight safety, and maintain airline serviceability.

Index Terms – Airline Operations, Aviation, Crew Resource Management, Model Human Processor, Single Pilot Cockpit

I. INTRODUCTION

Transportation is a large percentage of the US economy with commercial aviation accounting for 4.9 – 5.2% of total US GDP [1]. Commercial aviation representing a large part of the economy is an indicator of the significant operating overhead incurred. Operating costs for commercial airlines' domestic operations were \$133.6 billion dollars alone in 2012 [2]. The FAA estimates there will be an average increase in domestic air capacity of 2.1% per year over the

next twenty years and an average growth of 2.0% per year by mainline carriers over the next twenty years [3].

Over the last 12 years the number of major air carriers has shrunk from ten to four due to bankruptcies and mergers [5]. A noticeable trend is the industry's reaction to market and world events such as the dot-com bubble, 9/11, and the 2008 financial crisis.

Total operating expenses have grown steadily over the last two decades with several noticeable spikes during the last decade. The proportion of total operating costs for pilot labor has remained relatively static from 1990-2012 at an average of 6.8% [2]. Pilot labor costs are within the control of airline management and can be manipulated to reduce costs.

The Federal Aviation Administration (FAA) has predicted a six percent growth in demand for pilots between 2012 and 2022 [3]. Due to various changes in regulation, such as increasing mandatory flight hours, there is an increasing gap between forecasted supply and demand [4]. A single pilot cockpit system may help reduce the impact to a projected pilot shortage and bring some stability for future labor supply.

Removing pilots from the cockpit has been a strategy used in the past to reduce labor and operating costs. At the beginning of commercial air transport, a typical cockpit contained five pilots, each filling a distinct role. Over time, the roles of navigators, flight engineers, and radio operators have been eliminated [6]. 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.

II. STAKEHOLDER ANALYSIS

The stakeholders for the system were identified and categorized into three categories: regulatory agencies, aviation workforce, and the customer base. All of the groups have objectives, which may act as positive or negative forces to the system.

Commercial air carriers are driven by their business objectives to make profits and lower/control costs to attract and preserve investment into their industry. A single pilot cockpit would be agreeable for airlines for its potential to lower costs, but would meet resistance from the FAA, labor constituencies, and the customer base.

The FAA is responsible for maintaining a safe and efficient airspace. The inherent risk posed from removing a pilot from the cockpit promotes a change to the National

Airspace System – an idea which would meet heavy skepticism on behalf of the FAA.

Pilots would be hesitant to embrace a change to their work environment, especially when a reduction in the number of pilots is proposed. Air Traffic Control (ATC) will be concerned about workload increases through training or routine operations. If the single pilot cockpit begins to impact the ability to maintain a safe air space, both regulatory and labor groups may have serious objections.

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.

III. PROBLEM AND NEED STATEMENT

If commercial airliners have a more predictable and controllable cost portfolio, it may bring stability to their financial outlook. Savings and improved cost control could improve the overall financial health of airlines.

As the number of available pilots decreases, the cost for pilot labor could increase and lead to other negative cost/revenue burdens such as decreased flights and reduced serviceability. 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 thinner. Commercial airlines need to implement a system that will reduce operating costs to free up capital for other expenses and increase revenue.

IV. DESIGN ALTERNATIVES

The design alternatives for the analysis are established based on a black box approach where emphasis is placed on system level capability rather than component or subsystem level design and performance. A special focus is placed on selecting hypothetical cockpit systems that will potentially answer the system need and not fail reliability or cost before committing to any analysis. In that manner, not every possible design is considered, but only a few which appear reasonable to implement in the near future.

A. Baseline Two Pilot Cockpit

The baseline cockpit system shall be the two pilot cockpits. The baseline represents the “no change” option decision makers would hypothetically have. The option establishes cost, reliability, and procedural standards which other designs will be compared against. The majority of aircraft used for domestic air transport require, at a minimum, two pilots to fly. Some aircraft may have requirements for larger crew sizes, but those fall outside the scope.

B. Single Pilot with No Additional Support

The removal of a pilot from the cockpit with no additional technology to augment the roles of the lost co-pilot represents a low cost and low effort integration alternative. Presumably, when the co-pilot is eliminated, the remaining pilot will inherit more work but will also experience some

reduction from the absent need to interact with another entity. A study by the FAA on single pilot workload management found that pilots do experience increased workload and errors when flying alone but recommend resource management to better adapt the pilot to the changed flight dynamic. [7]

C. Single Pilot with Onboard Procedure Support

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 the FCOM. Automated tasks will fill the void left by the absence of a co-pilot.

VI. METHOD OF ANALYSIS

Three important factors are analyzed through modeling and simulation: how flight procedures change for each design, what are the cost requirements for each design on a per aircraft basis, and how does the system reliability change when a pilot is removed from the cockpit.

A. Procedure Model

Procedure models offer insight into how users operate a system and can be used under certain conditions to predict performance. 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 alternatives’ performance. A separate procedure model is created for each design alternative and serves as input to the procedure simulation. The best method for experimenting and testing flight procedures is with real pilots, a model for human interaction is used as a surrogate with the assumption it roughly approximates real flight scenarios.

The procedure model represents the standard operating procedure for flying a passenger jet aircraft. We first extract each procedure section from a RJ100 operating manual into an Excel spreadsheet to identify the responsible entities to execute a task. The procedure model is decomposed further into a custom XML schema so that it can later be parsed into the simulation program. A separate model was created for each design alternative to serve as input to the simulation.

The tasks which make up procedures are composed of specific physical and/or mental actions to be performed by one or both pilots. Our analysis developed a custom ontology for actions, which are described in Table 1.

When developing the derived procedure models for each alternative, tasks (and component actions) were manipulated based on how the cockpit was altered; i.e. a single pilot or a single pilot with avionics to automate *some* of the co-pilot workload.

TABLE I
PROCEDURE DECOMPOSITION ONTOLOGY

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

B. Procedure Simulation

The simulation is coded in Java with several additional libraries to provide enhanced functionality. The program begins by loading each procedure model and parsing the XML structure into different classes. The procedure structure is preserved through the simulation program structure. In this way, several procedure models can be loaded and ran sequentially. Procedures are executed through the iteration of each task and component action in a sequential serial fashion. Equation(1) captures the process by which an alternative processing time (APT) is generated.

$$\sum_{i=1}^j \sum_{k=1}^l \sum_{m=1}^n (Perception + Cognition + Motor)_{jln} \quad (1)$$

The underlying representation of the pilot is based upon the model human processor (MHP) of performance. The model is composed of the combination of perception, cognition, and motor elements from well validated human factors models such as ACT-R and GOMS [8]. The elements in the model notionally represent the processing time and capacity of a human with expert skill [8]. The three components of the model are represented by a network whose inputs are processed according to Table 2 which is adapted from Liu and Wu's model [8]. The processing times are representative of the human performance expected on a task. By serving input models into the simulation, the individual processing times are accumulated for each alternative. The output values are used to compare to the

baseline two pilot distributions of procedure processing times. Workload for the single pilot is measured as a ratio between the design alternative's processing time and the two pilot cockpit results.

The design of experiment in Table 3 shows the basic inputs for each alternative. The output distributions are not standard statistical curves and will be described in more detail in the results section.

TABLE II
HUMAN PROCESSOR NETWORK PROCESSING TIMES

Name	Time	Process
Eyes	50ms	Perception
VSen	N(263ms,10ms)	
Ears	10ms	
Asen	50ms	
CE	Exp(70ms)	Cognition
SMA	180ms	
M1	70ms	
PM	A+Bexp(-αN)	
BG		
Mouth	10ms	Motor
Hands	kLog(D/S+0.5)	
System Penalty	Exp(33..500ms)	Design Specific Processing Penalty

TABLE III
PROCEDURE SIMULATION DESIGN OF EXPERIMENT

Alternative	Input		
	Procedure Model	MHP Processing	Additional Processing Node
Two Pilot Baseline	$P_1 \dots P_n$ $T_{1m} \dots T_{nm}$	See Table 3	None
Single Pilot with No Additional Support	$P_1 \dots P_n$ $T_{1o} \dots T_{no}$	See Table 3	None
Single Pilot with Procedure Support	$P_1 \dots P_n$ $T_{1p} \dots T_{np}$	See Table 3	Exp(1/0.02)ms

Table 3: Design of Experiment for the procedure simulation

C. Business Case

The business model aims to determine the cost feasibility of each design alternative. A 25 year lifecycle model is constructed for an aircraft to model how much money can be potentially saved by eliminating a pilot from the cockpit. The per-aircraft savings is assumed to be the feasible investment amount (per aircraft) for the design alternative to meet the system need.

The lifecycle model is based on the operating cost of the most popular commercial jet airliner – the Boeing 737-300 [2]. In the model, an aircraft cost of \$90 million dollars is assumed with a 25% recovery rate. Maintenance costs and labor costs are derived from DoT Form 41 reporting for the scoped air carrier fleet. The model is represented in (2) which includes terms for a hypothetical escalation rate due to pilot labor shortage.

$$ALC = C_{Alt} + C_{Pilot_0} \sum_{t=1}^N \left(\frac{1+e}{1+d} \right)^t + \sum_{t=1}^N \frac{C_{Maintenance}}{(1+d)^t} - \sum_{t=1}^N \frac{C_{Residual}}{(1+d)^t}$$

C_{alt} = alternative unit cost C_{Pilot} = pilot cost
 C_{Maint} = maintenance costs $C_{Residual}$ = salvage value
 e = escalation rate d = interest rate

(2)

The model has parameters such as interest and escalation rates are varied to provide a feasible range of values under different conditions which can vary by management and economic factors. The best case and worst case values are determined based on the model. For analysis purposes, the best case scenario is chosen for cost savings based on the assumption that airlines would make their decisions based on the same line of thinking.

TABLE IV
BUSINESS CASE DESIGN OF EXPERIMENT

Inputs			
Alternative	Alternative Cost	Pilot Cost	Maint Cost
Two Pilot Baseline	$C_A = \$0$	$C_P = \$141,927$	$C_M = \$9.127M$
		$E=0.05\%-5\%$	
Single Pilot with No Additional Support	$C_A = \$0$	$C_P = \$269,126$	$C_M = \$9.127M$
		$E=0.05\%-5\%$	
Single Pilot with Procedure Support	$C_A = \$100K, \$4.38M$	$C_P = \$141,927$	$C_M = \$9.127M$
		$E=0.05\%-5\%$	

D. Reliability Case

In an effort to find the feasible space for each alternative, the mean time between failures is varied as an input to the reliability block diagram. For all analysis, the reliability at one million flight hours is considered. The baseline aviation reliability at one million flight hours was derived from NTSB accident reporting for domestic operations. The average amount of accidents per million flight hours was treated as a failure rate with $1/\lambda$ representing the mean time between failures (MTBF) calculated to be 0.8674[9]. When comparing the reliabilities of each alternative, the regions that meet or exceed this baseline value are assumed to maintain or improve flight safety.

The failure rates are varied to generate a range of potential combinations for overall system reliability. This analysis is geared towards establishing what safety level a design alternative must meet to be considered possible for airspace integration.

Equation(3) and (4) shows the two arrangements of series and parallel system component reliability respectively. Each alternative is configured and instantiated per the design of experiment in Table 5.

$$R_s(t, R_{1..n}) = \prod_{i=1}^n R_i = \exp\left(\frac{-t}{\sum_{i=1}^n R_i}\right) \quad (3)$$

$$R_p(t, R_{1..n}) = 1 - \prod_{i=1}^n (1 - R_i) \quad (4)$$

TABLE V
RELIABILITY MODEL DESIGN OF EXPERIMENT

Input			Output
Alternative	Cockpit Failure Rate	Aircraft Failure Rate	Required Reliability
Two Pilot Baseline	$\lambda_c = 1.0..0.1$	$\lambda_A = 1.0..0.1$	$R_s = R_A R_P$
Single Pilot with No Additional Support	$\lambda_c = 1.0..0.1$	$\lambda_A = 1.0..0.1$	$R_s = R_A(R_{P1}+R_{P2}) - R_{P2}R_{P1}$
Single Pilot with Procedure Support	$\lambda_c = 1.0..0.1$	$\lambda_A = 1.0..0.1$	$R_s = R_A R_P R_{Alt}$

VII. RESULTS

Results were collected for the three different analyses and compiled as inputs to a value-hierarchy model. Using a weighted scoring method, a recommendation was made based on a cost vs. utility ranking.

A. Procedure Simulation

After running the simulation for each alternative 1000 times, statistics were collected to describe the behavior of the resulting output. The procedural simulation showed that tradeoffs between workload and processing time occurred for each alternative. Figure 1 represents a sample of ten procedures and the output processing times for each alternative. Just by visual inspection and intuition, the single pilot has decreased the amount of time to complete a procedure (due to the reduction in tasks) though a lone entity is executing the tasks entirely versus when there is an onboard support system handling some of the work.

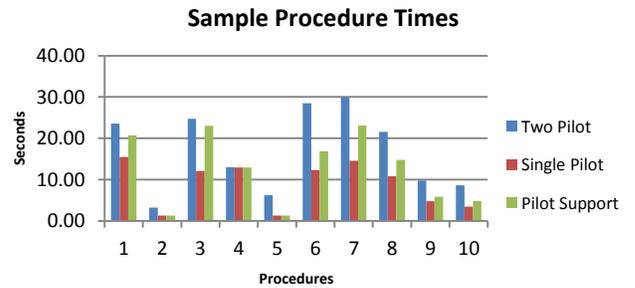


FIGURE I
SAMPLE OF TEN DIFFERENT PROCEDURES AND THEIR ASSOCIATED PROCESSING TIMES

A histogram was created for all the procedure processing times as shown in Figure 2 Three separate statistical tests: Kolomogrov-Smirnov, Cramer-Von Mises, and Anderson-Darling were performed to test if the data followed a normal, lognormal, exponential, or gamma distribution.

There was not enough statistical to suggest the data followed any of the target distributions.

Hypothesis testing was performed to evaluate if there was a difference in the mean procedure processing times between each alternative and the two pilot cockpit baseline case. A t-test, sign, and sign-ranked test were performed to test the hypothesis. Results for all tests showed that there was a significant difference in mean processing times with a P-Value < 0.001 for each alternative.

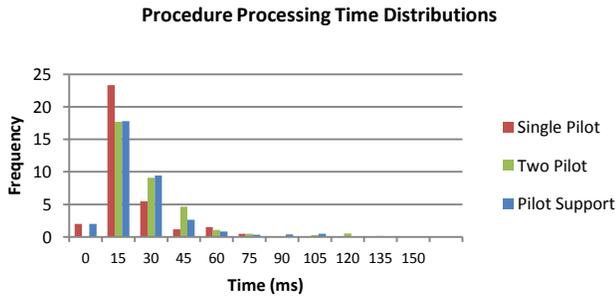


FIGURE II
HISTOGRAM OF AVERAGE PROCEDURE TIMES

Intuitively, a significant difference would be expected due to the reduction in tasks to perform procedures for each alternative. To better understand the problem, the average workload (alternative procedure time divided by baseline procedure time or time required divided by time allowed) was calculated. Figure 3 shows the workload for each procedure. The single pilot with no support incurred an average workload of 4.27 ± 1.7 and the average single pilot with onboard support workload was 0.75 ± 0.13

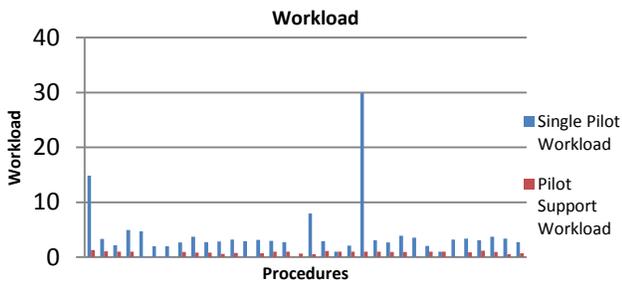


FIGURE III
WORKLOAD FOR EACH ALTERNATIVE USING BASELINE TWO PILOT COCKPIT AS THE "TIME ALLOWED" PARAMETER

Taking the average workload as an indicator of risk, the single pilot flying with no support will spend more effort in flying, though will take less time to execute procedures whereas the single pilot with an onboard support system will see a reduction in the effort, but little or no change to the amount of time to execute procedures.

B. Reliability Case

The reliability analysis was conducted to show the overall system reliability as a function of the cockpit and aircraft reliability. The two pilots (in parallel) will have a range of failure rates that they can maintain to produce output cockpit reliability. To meet or exceed the target rate of

0.8674, the alternative must meet a feasible reliability above ~0.80 (assuming 0.95 or greater reliability of the aircraft). The output in Figure 4 shows where the reliability requirement would have to be established given a fixed aircraft and overall target system reliability. In constructing a range of failure rates for each alternative, the results incorporate sensitivity based on how much an alternative's reliability changes with respect to the overall system and vice versa. By conducting the analysis in this manner, a boundary requirement is established for the system to meet.

The reliability for the single pilot with no additional support and single pilot with procedure support significantly reduced relative to the baseline two pilot cockpit. Decreasing the failure rate to a higher level or adding a functional capability to the system to self-land an aircraft during a pilot incapacitation would drastically improve the reliability of the alternatives.

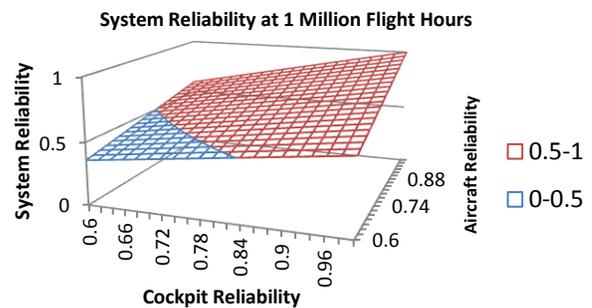


FIGURE IV
RELIABILITY AT ONE MILLION FLIGHT HOURS AS A FUNCTION OF THE OUTPUT RELIABILITY FROM THE COCKPIT ALTERNATIVE AND AIRCRAFT SYSTEM

C. Business Case

The business case output a range of values which can be used to establish a feasible space for investing into an alternative on a per-aircraft basis, or would represent savings should the single pilot with no additional support be chosen. The analysis, shown in Figure 5, showed that the range of savings captured is between 1.25 and 4.38 million dollars per aircraft. The results were varied based on interest rate and escalation rate to give a range of potential values under different circumstances.



FIGURE V
FEASIBLE SAVINGS BASED ON VARIED INTEREST AND PILOT ESCALATION RATES

VIII. RECOMMENDATION AND CONCLUSION

Recommendations were made based on a value hierarchy and cost/utility function shown in Figure 6. Alternative processing time and workload risk were determined based on output data from the procedure simulation and normalized based on a linear function. Workload risk represented the ratio of an alternatives procedure time to the baseline two pilot cockpit procedure times, i.e. time required vs. time available. Reliability was a binary 1 or 0 based on the alternative's ability to maintain or improve safety. The attributes were weighted to produce a utility score for each alternative. Weights were derived from stakeholder analysis and sponsor input.

The resulting alternatives were calculated to have the highest to lowest utility in the following order: two pilot cockpit (no change), single pilot cockpit with onboard support, and the single pilot cockpit with no support. The utility with selecting the single pilot alternative is the lowest due to the increase risk from reduced cockpit reliability and increased workload. The single pilot with onboard support system has roughly the same utility as the baseline cockpit, but potentially offers improved aircraft operating costs.

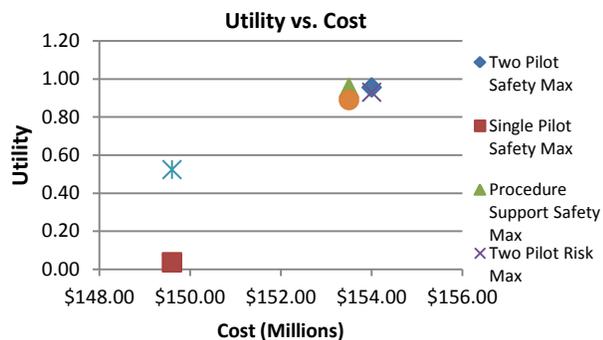


FIGURE VI
COST-UTILITY ANALYSIS RESULTS

The single pilot with procedure support was determined to be a possible cost saving solution for airline management, but would require significant qualification and verification before it could fully transition to full operations. The ability for the system to override a pilot in emergency situations (like pilot incapacitation) would be required should the system be integrated into the aircraft cockpit. The single pilot with no support would be too risky to implement with respect to flight safety while doing nothing would not satisfy the system need though flight safety would remain unchanged relative to the current system.

If pilot reliability were discounted or the pilot reliability proved to be feasible, then the single pilot cockpit would capture the most cost savings and approach the utility of a single pilot cockpit with an onboard support system or the two pilot cockpit. Flight safety is too paramount to discount and will critically impair any changes to the flight deck without compensating for the lost pilot's flying ability during the event of pilot incapacitation.

Long term evaluation is recommended to slowly transition and adopt a single pilot cockpit. Within the transition period, careful evaluation could be made to improve and refine the design while satisfying stakeholder tensions. A single pilot cockpit would mitigate the effects of pilot labor shortage and bring better predictability and stability to commercial aviation operating budgets.

Further analysis for cockpit interactions would be required to validate the results of the procedure modeling and simulation. If the results are statistically significant, procedures can be easily designed and tested through the simulation as an indication of cockpit workload and resource management.

ACKNOWLEDGEMENT

The authors would like to thank Mr. Andrew Lacher (Mitre CAASD) for his contributions as the sponsor of this project. Also, special thanks to instructors Dr. Lance Sherry, Ms. Paula Lewis, and Mr. Jedidiah Shirey (GMU).

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