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A Simulation Modeling the Effects of Maintenance Personnel on Aircraft Sortie Generation

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THESIS

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THESIS

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Abstract

Commanders and wargamers lack adequate tools to quickly determine the number of mission-capable (MC) aircraft and number of achievable sorties to support wargames and exercises. Even less understood is the impact of available maintenance personnel on sortie generation. The Expected-Number-of-In-Game-Mission-capable Aircraft (ENIGMA) simulation was recently developed to calculate the number of MC aircraft and number of sorties flown accounting for the number and type of aircraft, scheduled sorties, mean-time-between-failure (MTBF), and mean-time-to-repair (MTTR). ENIGMA is extended by replacing the MTTR input with functions derived from actual numbers and types of maintenance personnel available. Functions in the form of response surface models are created for each aircraft using data output from the Logistic Composite Model (LCOM), applying both a normal distribution and a Weibull distribution to account for model fit errors. The statistical distribution assumed for the residual errors of the model fit greatly affects model adequacy. Operationally, four scenarios are developed changing the number of personnel, number of aircraft, and number of sorties flown. These scenarios result in concluding there is a statistically significant difference between the normal and Weibull prediction functions for average number of MC aircraft. Regardless of distribution, a large difference in number of MC aircraft and number of sorties flown between minimum and median personnel levels is observed, but not a large difference between median and maximum personnel levels. The enhanced ENIGMA simulation provides the impact of evolving operational scenarios to include how available maintenance personnel affect sortie generation. The improvements to ENIGMA through implementation of these functions provide the ability to better understand the impact of available maintenance personnel on sortie generation along with the original understanding of the impact of aircraft use.

To my wife

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Foremost, I would like to express my sincere gratitude to my advisor, Dr. Ahner. Without his guidance, mentorship, encouragement, and patience finishing this thesis would not have been possible.

Benjamin D. Huffman

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A SIMULATION MODELING THE EFFECTS OF MAINTENANCE PERSONNEL ON AIRCRAFT SORTIE GENERATION

I. Introduction

1.1 Motivation and Background

The Summary of the 2018 National Defense Strategy (NDS) (Mattis [2018]), calls for increased readiness to protect our nation against near-peer adversaries. It is foreseeable to project Air Force forces to forward locations that constrain the availability of logistics and maintenance personnel. As aircraft are used, they experience maintenance failures. These failures require maintenance personnel and logistics along with time to achieve corrective action. The mission-capable (MC) aircraft measure and the ability to generate sorties as desired by the operation are two measures of operational readiness. Maintenance personnel, break rates, and repair times play an immense role in determining the availability of weapon systems accessible to commanders. Scenarios that provide insight to these operations should be closely studied with a specific focus on how maintenance manpower affects break rates, repair times, and sortie generation in achieving the NDS goals. One way of studying the effects of maintenance manpower is by building models that account for varying factors such as number of personnel, quantity of aircraft and sorties, break rates, and repair times. Creating a model that can quickly determine expected MC aircraft and sorties flown and account for the number of maintenance personnel available, achieves the insights needed towards understanding aircraft sortie generation capabilities.

1.2 Problem Statement

Air Force leaders require a logistics wargaming tool to determine the effects of break rates, repair times and available maintenance manpower on aircraft sortie generation. The simulation tool should account for real-world situations and wargaming conditions. This includes the attrition and buildup of aircraft, personnel, and equipment. This logistics wargaming tool should also provide output that gives expected MC aircraft and sortie numbers based on the maintenance manning level.

1.3 Research Questions

The main goal of this thesis is to determine how maintenance manning affects sortie generation. This effort is achieved by answering the following research questions.

1. Can adequate models be developed from LCOM input to account for types and numbers of maintenance personnel?
2. Can these LCOM response surface models be validated?
3. Is there a difference between the normal and Weibull distributions assumed for the errors in response surface models?
4. Can the models of LCOM be integrated into ENIGMA and provide realistic operational insight?

1.4 Organization of the Thesis

This thesis is organized into five chapters. Chapter I addresses the background, problem statement, and research questions. Chapter II discusses the literature review and previous work done in related topics. Chapter III is the solution methodology developed to construct the models and implement them into ENIGMA. Chapter IV

reveals the testing, results, and analysis of the developed scenarios. Chapter V provides conclusions and contains recommendations of the accomplished research.

II. Literature Review

This chapter discusses related and previous work accomplished in sortie generation processes and models, the Logistics Composite Model (LCOM), discrete event simulation and metamodels, and finally space covering designs.

2.1 Sortie Generation

Many models have been built simulating the sortie generation process. The majority of these models focus on either predicting or improving mission-capable (MC) rates, although the focus and input data for each of the many models vary. For example, in his thesis, Faas [2003] focused on reducing the time to repair an aircraft by modeling an autonomic logistics system (ALS). The sortie generation process described and used by Faas [2003] can be seen in Figure 1.

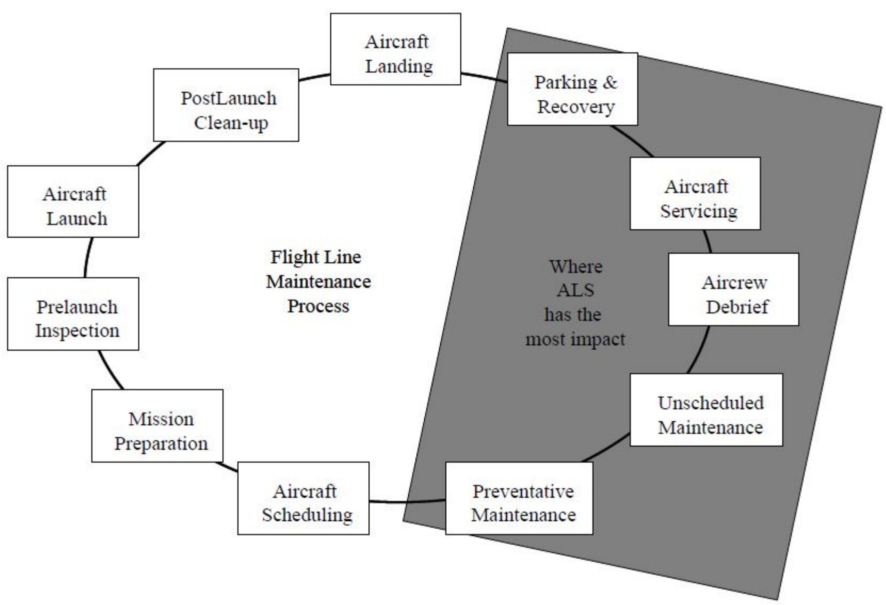


Figure 1. Sortie Generation Process from Faas [2003]

Maintenance personnel play a role in every step in Figure 1 and thus have a huge

effect on the sortie generation process. By using an ALS, the aircraft can detect a broken part, notify maintenance, and order the part, all before the aircraft lands. This gives maintenance repair teams a head start on fixing the aircraft (Faas [2003]). The goal of Faas' model is to determine how the use of an ALS affects sortie generation.

The inputs to Faas's model are sortie duration, pre-flight failure rate, supply level, order level, takeoff times, number of aircraft, ALS settings, and mean-time-between-failure (MTBF). There are many outputs to this model including MC rate, number of sorties flown, and utilization rate. Additional outputs can be seen in Table 1. Faas [2003] concluded, "The results of this research showed that the ALS equipped aircraft can perform better than a non-ALS aircraft up to a point (Faas [2003])." The sooner maintenance learns of a break, the sooner they can begin a repair, which reduces the overall mean time to repair an aircraft.

Another model created by Chimka and Nachtmann [2007] uses regression modeling with number and percentage of maintainers by skill level as the independent variables and various maintenance metrics as the dependent variables. Maintenance skill levels are classified as 3, 5, 7, and 9-levels. Three-levels are novice maintainers still undergoing on-the-job training. Five-levels typically have 1-2 years of maintenance experience and have completed certain training tasks. They are able to perform more difficult maintenance tasks and have the ability to work with minimum supervision. Seven-levels hold the rank of at least Staff Sergeant and are considered experts in their field. 9-levels are at minimum Senior Master Sergeants and hold leadership positions in their maintenance unit. Percent of 7 and 9-levels and number of 3, 5, 7, and 9-levels are the inputs while MC rate, fix rate, and other metrics (see Table 1) are the outputs. The main focus is on using regression to predict MC rates. They found that using percentage of 7-levels and 9-levels, it is possible to build a model that explains 82% of the variance in MC rates. Chimka and Nachtmann [2007] also

found a range of MC rates for different combinations of percentages of 7-levels and 9-levels. This model indicates experience of maintainers plays a significant role in MC rates.

MacKenzie et al. [2010] used an agent-based model to simulate an F-16 squadron. His focus was on building an accurate model using agent-based modeling to better understand the interactions between different AFSCs that affect sortie generation rather than optimizing manpower or maximizing MC rates. Inputs for MacKenzie's model include different agent types such as aircraft, production supervisor, expediter, maintainer, and also supporting metrics. MacKenzie et al. [2010] used this model to calculate the utilization and production capacity of maintenance. MacKenzie's agent-based model is better able to capture the complex interactions within a unit that affect aircraft production. One finding was that small differences in these interactions between agents can significantly impact sortie generation over time.

Gotz and Stanton [1986] discuss a basic queuing model relating maintenance personnel to weapon system availability with a focus on cross training. They modeled three scenarios: 1) a base case 2) higher failure rates and slower repair rates and 3) inclusion of spare parts allowing broken parts to be removed and replaced on the aircraft with a reduced repair time. The main focus of the model is on cross-training and skill level. Each member in the model has a primary and secondary skill along with a skill level to determine the effect on weapon system availability. A higher skill level is equated to shorter repair times. Required inputs are number of repairmen, length of repair, break rate, number of spares, number of aircraft, and aircraft loss rate. This model outputs available aircraft, repair cycle times, and MTTR. They found that cross training only had a small effect; roughly 2 more aircraft (52 versus 54) over 13 days. Including spare parts with cross training provided about 7 more aircraft (47 versus 54) over 13 days. Cross-training is another factor that affects sortie

generation.

The Sortie Generation Rate model was developed by Harris [2002] for intended use at the air base level to calculate metrics quickly and easily. A variety of inputs are needed, including number of flying days, number of aircraft, number of aircrew, sortie duration, aircrew rest, and others found in Table 1. Of note, many aircrew factors rather than maintenance factors are used in this model. Harris [2002] predicted daily sorties flown, sortie rate, and utilization rate. All models built to predict these metrics are within the 95% confidence interval of actual data. Harris [2002] brought to light that more than just maintenance factors may affect sortie generation. These factors include number of aircrews, aircrew duty day in hours, consecutive day flying hour limit, max sorties per day per aircrew, end of duty day mandatory crew rest, and extended crew rest.

Oliver [2001] used regression to successfully predict MC rates for F-16 squadrons. The final functional form is shown in Equation 1.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_{10}/X_{12} + \varepsilon \tag{1}$$

The functional form parameters are explained below.

Predicted Y: F-16C/D Mission Capable Rate

Original Effects:

X_1 = TNMCM Hours of Wtd Top 50 WUCs

X_2 = Cannibalization Hours of Wtd Top 50 WUCs

X_3 = Average Aircraft Inventory

X_4 = Total F-16 Maintenance Personnel Assigned (Lag 0)

X_5 = Total 3-Levels Assigned (Lag 0)

X_6 = Total 7-Levels Assigned (Lag 0)

Interactions: X_{10}/X_{12} = 3-Levels Assigned/7-Levels Assigned

Higher order terms: No significant higher order terms were revealed

The important variables are total non-mission-capable for maintenance hours, cannibalization hours, average aircraft inventory, along with total number of personnel, number of 3-levels, number of 7-levels and the ratio of 3-levels to 7-levels. This model allows MC rates for the F-16 to be predicted inside a 95% confidence interval 100% of the time. The paper concludes that grade and skill are the major factors in increasing MC rates as seen by the 3-level, 7-level, and 3-level to 7-level ratio factors. Oliver [2001] concluded, "The results of the analysis were very similar to the findings of other studies that analyzed how personnel levels relate to mission capable rates. The underlying factor in the personnel data appeared to be experience. Whether the data was analyzed by grade, skill level or percent of authorizations filled, the story was the same as the number of inexperienced personnel (defined as 3-levels and E-3s) increased, mission capable rates decreased. Conversely, as experience increased (5, 7 and 9 levels as well as E-4 E-9) mission capable rates increased."

Moore [1998] determined which maintenance characteristics increase and decrease MC rates for the United States Navy. Increasing factors are number of sorties flown, and the interactions between direct aircraft maintenance man-hours per flight hour

and number of sorties flown, number of enlisted personnel and percent of crew who make E-5 in 4 years or less, percent of items beyond capability of maintenance and sent to depot and percent of crew with M+1 requirements weighted by paygrade, and lastly the number of enlisted personnel and percent of crew who scored in upper mental group on AFQT. The decreasing factors are percent of items beyond capability of maintenance and sent to depot, number of canns in a month per 100 flight hours, number of enlisted personnel, percent of crew who scored in upper mental group on AFQT, and the interactions between the number of canns in a month per 100 flight hours and number of sorties flown, and finally elapsed maintenance time per maintenance action and percent of crew who make E-5 in 4 years or less. This continues to show that number of personnel and experience play a role in determining MC rates.

In the article "Beyond Authorized Versus Assigned Aircraft Maintenance Personnel Capacity", Howe et al. [2009] introduce using a new term, net effective personnel (NEP), instead of the usual authorized versus assigned ratio to determine manpower. NEP uses estimates for personnel effectiveness using weights based off of skill level since a 3-level is not as effective as a 7-level. They also take trainers into account by decreasing their effectiveness. The inputs to the NEP equation are a 7 and 5-level ancillary computer based training (CBT) factor, number of available 7 and 5-levels who are not trainers, trainer productivity, number of 7 and 5-level trainers, a 3-level ancillary CBT factor, trainee productivity, and number of available 3 levels. By substituting these inputs into the NEP equation (Equation 2), a unit's NEP can be determined.

$$NEP = T_{75}(A_{75NT} + (P_T A_{75T})) + T_3(P_e A_3) \tag{2}$$

NEP is more accurate than authorized over assigned because not all authorized

or assigned personnel perform maintenance (Howe et al. [2009]). This again shows skill level and ratio of skill levels are important factors.

Dietz [1985] used statistics to determine distributions for mean-sorties-between-failure (MSBF) and mean-time-to-repair (MTTR) of aircraft. Generally, it was found that repair times follow a lognormal distribution. He used the probability distribution of subsystem failure time (exponential distribution) to determine a new probability distribution. Dietz [1985] also found that improving reliability does not necessarily improve availability: "...improvement in aircraft reliability yields a substantially decreasing marginal return in availability." A relationship between mean repair time and reliability was also discovered and according to Dietz [1985] "Reduction in mean repair time appears to offer considerable benefit, particularly at low reliability levels." This means as reliability (MSBF) increases, MTTR decreases. Figure 2 from Dietz [1985] depicts a plot with Change in Mean Repair Time on the y-axis and Aircraft Reliability (MSBF) on the x-axis. At low reliability levels, there is an increase in mean repair time of around 0.3 hours. At high reliability levels, there is only a slight increase of about 0.02 in mean repair time. "Figure 7.1 [Figure 2] indicates that even severe manpower constraints have virtually no impact on mean repair time for a highly reliable system (Dietz [1985]) ..." For further work, Dietz [1985] recommended looking at repair time distributions for separate subsystems instead of the whole aircraft.

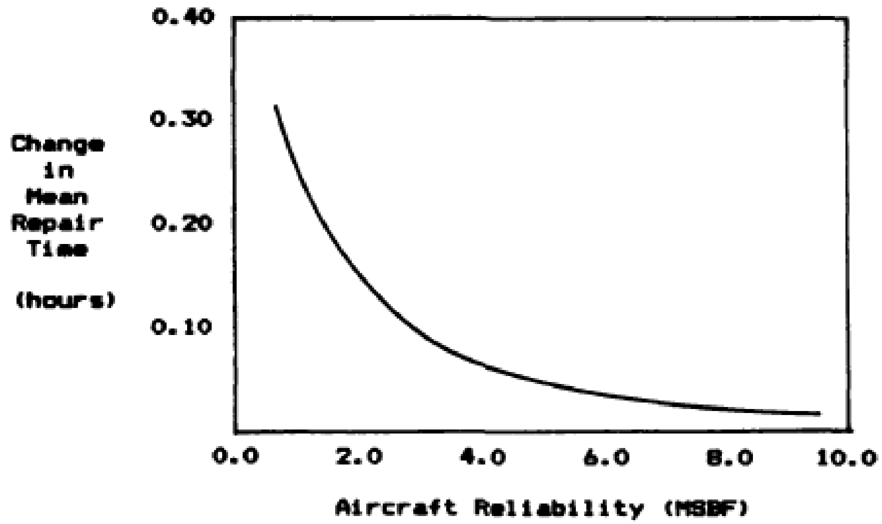


Figure 7.1. Impact of Manpower Constraints vs. Aircraft Reliability

Figure 2. Figure 7.1 from Dietz [1985]

Table 1 displays a comparison of each of the models discussed. It includes the author, model goal, inputs, and outputs. This table makes it easier to perceive the small differences between each of the models. These models provided many insights on possible important factors in determining accurate MC rates. Starting repair times sooner, skill level and experience of maintenance personnel, number of personnel, interactions between personnel, cross-training, aircrew factors, and many more factors significantly affect sortie generation.

Table 1. Comparison of Discussed Models

Author	Model	Objective	Approach	Input	Output
Faas	Autonomic Logistics System (ALS)	Simulate F-16 aircraft sortie generation operations using ALS	Simulation	Sortie duration Preflight Failure Rate Supply Level Order Level Takeoff Times Number of aircraft ALS Settings MTBF	Possessed Hrs AVG Possessed ACFT MC Hours MC Rate NMCM Hours NMCM Rate NMCS Hours NMCS Rate Sorties Scheduled Sorties Flown Hourly UTE Rate Sortie UTE Rate Hours Flown Flying Sch Eff Rate Air Aborts Ground Aborts Abort Rate
Chimka & Nachtmann	Multiple/Linear Regression	Measure MC rate as a function ofMaintenance personnel	Regression	% 7-levels % 9-levels # 7-levels # 5-levels # 3-levels # 9-levels	MC Rate 8-hour Fix Rate Average Aircraft Inventory CANN Hours Maintenance Reliability TNMCM Hours
MacKenzie	Agent Based Model	Explore effects of maintenance manning on combat mission readiness	Simulation	Aircraft Agents Production Supervisor Agents Expediter Agents Maintainer Agents Supporting Metrics	Utilization and production capacity of maintenance
Gotz & Stanton	Queing Model	Relate skill level and cross training to measure performance	Simulation	Number of repairman by skill level Length of Repair Break Rate Number of Spare in system Initial number of aircraft Aircraft loss rate	Available Aircraft Repair cycle time Average time of repair
Harris	Sortie Generation Rate Model	A commander's tool to generate sortie rates for planning options	Simulation	Number of days sorties will be flown Number of aircraft Number of aircrews Crew duty day length Prebriefing and postbriefing time Aircraft amintenance time Number of aircraft maintained simultaneously Sortie duration Aircrew rest Limits on aircrew cumulative flying hours	Utilization rate Sortie rate
Oliver	Final Explanatory Model	Predict MC rate of F-16 aircraft	Regression	TNMCM Hours of Top 50 WUC's Cann Hours of Top 50 WUC's Average Aircraft Inventory Total F-16 Mx Personnel Assigned Total 3-levels Assigned Total 7-levels Assigned 3-levels Assigned/7-levels Assigned	F-16 MC rate
Moore	Logistic Regression (No AVCAL Variables)	Predict aircraft readiness	Regression	Number of sorties flown Direct maintenance man-hours per flight hour and Number of sorties flown Number of enlisted personnel and Percent of crew who make E-5 in 4 years or less Percent of items beyond capability of maintenance and sent to depot and Percent of crew with M+1 requirements weighted by paygrade Number of enlisted personnel and Percent of crew who scored in upper mental group on AFQT	FMC Rates
Howe et al	Net Effective Personnel	Determine available capacity over a given time period	Equation	T75 = Ancillary/CBT Factor for 7- and 5-levels A75NT = The number of available nonmanager 7-levels and 5-levels who are not trainers Pt = Trainer Productivity A75T = The number of available nonmanager 7-levels and 5-levels who are trainers T3 = Ancillary/CBT Factor for 3-levels Pe = Trainee Productivity A3 = The number of available 3-levels	Number of Net Effective Personnel
Dietz	MTTR	Form a repair time distribution for the Advanced Tactical Fighter and other highly reliable advanced technology aircraft	Simulation	Subsystem failure time distributions (exponential)	Probability Distribution
Ahner, Choo, Huffman	ENIGMA	Determine expected number of available aircraft and number of sorties flown	Simulation	Maintenance Personnel AFSC's / MTTR ATO/Sortie Schedule Number and type of Aircraft Equipment/Supplies MTBF	Expected Number of In Game Aircraft Expected number of sorties flown

2.2 Logistic Composite Model (LCOM)

Boyle [1990] provides a thorough explanation of the Logistic Composite Model (LCOM). LCOM was created to explore the link between logistic resources and sortie generation. It has since evolved into determining maintenance manning requirements across the Air Force. LCOM is a simulation modeling tool that, given a certain number of resources such as spare parts, equipment, etc. and a desired sortie rate, determines the minimum number of personnel required to meet that rate (Boyle [1990]). There are many finer details as to how LCOM accomplishes this, but this is the basic purpose of LCOM.

Despite LCOM being the Air Force's main tool for determining maintenance manpower levels, it still has a fair share of shortfalls and assumptions. Dahlman et al. [2002] researched LCOM to determine the accuracy of the model. Dahlman et al. [2002] first describes the sortie generation process in Figure 3 used by LCOM. This is similar to Figure 1 and the process Faas [2003] used.

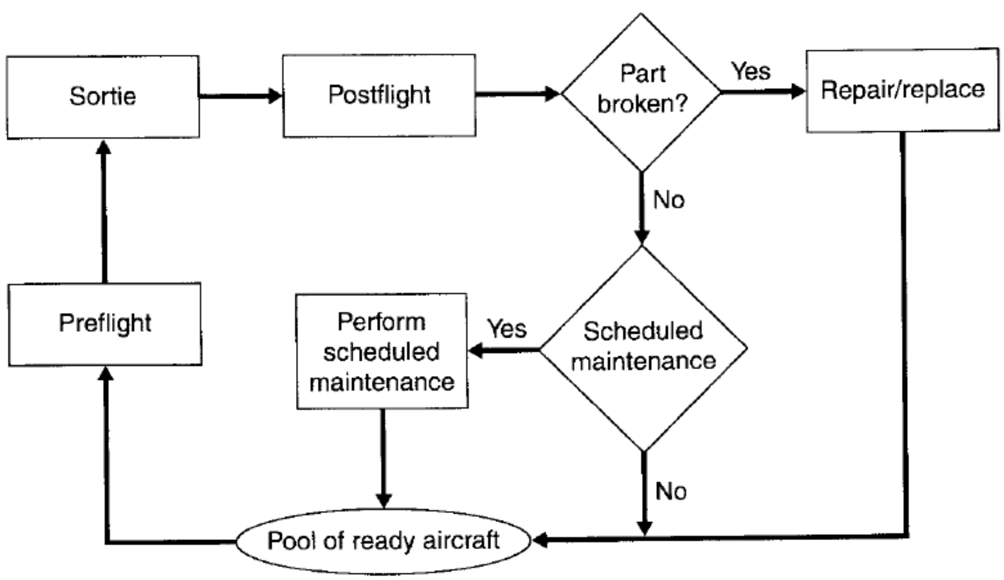


Figure 3.1—Simple Overview of the LCOM Process

Figure 3. LCOM Process from Dahlman et al. [2002]

A detailed look into the inputs and outputs determined there is a linear relationship between break rate and maintenance man-hours. However, just because man-hours increase, does not mean manpower requirements increase. "As one would expect, LCOM runs show that average maintenance man-hours scale linearly with maintenance action rates, at least until throughput constraints become binding. In other words, a 10 percent across-the-board increase in the break rates of all systems will result in a 10 percent increase in required maintenance man-hours. However, moderate man-hour changes may not alter the manpower requirements at all (Dahlman et al. [2002])."

While LCOM uses many factors to determine manpower requirements, Dahlman et al. [2002] found that MTTR should be the main factor in determining manpower. Something often misconstrued about LCOM, is that it does not *optimize* manpower. Just because there is a certain number of personnel assigned or authorized, it does not mean that is the best number of personnel because that number is just enough to simply satisfy the requirements."It is, at heart, a manpower planning tool that can be expected to ensure only that the manpower resources provided are not constraining the sortie generation requirement. Thus, the use of LCOM to determine manpower requirements is better described as a satisficing process, not an optimizing one (Dahlman et al. [2002])."

Returning to the linear relationship described between inputs and outputs, inputs include all resources not just maintenance manpower. But if manpower is increased, the output should also increase at least slightly. "LCOM represents maintenance as using resources - labor, spare parts, test stands etc. - to produce output: the repair and servicing of aircraft. Adding more of one of the inputs will result in an increased output per workday. In economic terminology, this effect is called the marginal product of the input. For small changes in the inputs, there will be a linear

relationship between inputs and outputs implying that the marginal product is a constant. This means that an increase of an input by x percent will result in an increase in the output by the same x percent." While it is true the change will be linear, it may be linear times some constant.

Another major finding by Dahlman was that there is a difference in determining cargo and fighter aircraft manning requirements. Cargo aircraft manning is based on minimum crew size while fighter aircraft manning should be based on break rates and MTTR. To summarize Dahlman et al. [2002], the binding constraints on the F-15C/D seem to be opposite of the binding constraints on the C-130. Minimum crew size will determine the manpower requirement for the C-130 while other factors such as break rates, task duration, and business rules will determine the shift manning for the F-15C/D.

Data quality is another problem in LCOM as not all breaks are written up accurately in data systems. For example, a more generic break such as hydraulic system may be used instead of a more specific maintenance action such as removed and replaced auxiliary hydraulic pump. Dahlman et al. [2002] suggests looking at the ratios and interactions of skill levels along with on-the-job-training (OJT) and out-of-hide positions to improve results, "More generally, current manpower processes should more systematically take force management into account. This report proposes several steps in this area, including paying much more careful attention to OJT and to the functionally required experience mix of 3-, 5-, and 7-level maintainers."

Although LCOM is a very useful tool in deciding maintenance manpower requirements, it is not 100% accurate. The intent behind LCOM is to give an idea of what manning requirements should be, not to provide the optimal manning requirements. This research also provides some explanation into the relationship between maintenance manning, break rates, and repair times.

2.3 Discrete Event Simulation and Metamodels

A simulation is a representation of a real-world system. Many experiments can be run in a simulation that may not necessarily be economically feasible or practical in the real system. It is important that a simulation accurately represents the system it models. This section explores how to build an accurate simulation, specifically a metamodel.

One important aspect used in this research is metamodeling. Ahner and McCarthy [2020] employ a metamodel. Using the outputs from one simulation, Ahner and McCarthy then use those outputs as inputs into another model. This is the definition of a metamodel - using one model to characterize another model.

Blanning [1975] uses metamodels for sensitivity analysis instead of using many simulation runs. Outputs from an initial decision model are part of the inputs to another model called a metamodel. According to Blanning [1975], metamodeling is computationally less effort than performing many simulations as it can find a Pareto frontier of solutions. However, no general method of constructing a metamodel exists. Blanning [1975] gives two methods and two examples of how to construct a metamodel. "The first and more useful approach is to examine some of the inputs and outputs of a simulation and to infer an appropriate functional form for the metamodel." "The second and usually less useful approach is to construct a simple analytical model (e.g., a queueing model or a renewal model) and to differentiate it." Blanning [1975]'s last recommendation given for metamodeling is to keep the model simple and small.

dos Santos and Porta Nova [1999] discuss the common problems with nonlinear metamodels. Metamodels simplify simulation models making inputs and outputs easier to interpret. Linear models are not always a good representation, but there are also issues with nonlinear models. dos Santos and Porta Nova [1999] give a very

basic description of modeling: "The approach is: (i) we first choose, for the model, a function that may closely follow the output variable Y , throughout the region to which the data belong; then, (ii) we estimate the parameters of the elected model; and, finally, (iii) we investigate if the model is, in fact, adequate or not." Validation is perhaps the most important part of modeling. Validation examines if the metamodel accurately describes the simulation. This can be done in different ways such as a lack-of-fit test or cross-validation and data-splitting (dos Santos and Porta Nova [1999]). dos Santos and Porta Nova [1999] recommend the process of:

1.) Identify a tentative nonlinear relation between the response and decision variables.

2.) Select a curve from a catalog of typical nonlinear functional relationships.

3.) Estimate the nonlinear simulation metamodel.

4.) Validate the nonlinear simulation metamodel.

Kleijnen and Sargent [2000] also developed a method for building metamodels which identifies the relationship between the problem entity, simulation model, and metamodel. Kleijnen and Sargent [2000] describe the following 10-step method:

1.) Determine the goal of the metamodel

2.) Identify the inputs and their characteristics

3.) Specify the domain of applicability

4.) Identify the output variable and its characteristics

5.) Specify the accuracy required of the metamodel

6.) Specify the metamodels validity measures and their required values

7.) Specify the metamodel and review this specification

8.) Specify a design including tactical issues and review the DOE

9.) Fit the metamodel

10.) Determine the validity of the fitted metamodel

Detailed explanations of some of the steps can be found in their article (see Kleijnen and Sargent [2000]). To summarize Kleijnen and Sargent [2000], a metamodel has four goals: 1) understanding 2) predicting 3) optimizing and 4) validating/verifying.

Metamodeling is a useful tool that can simplify models and can enable embedding lower level model outputs into more complex models. Methods also exist that help in constructing accurate metamodels.

2.4 Space Covering Designs

Space covering designs are models that optimize a relationship between a response variable and one or more independent variables by performing a series of experiments.

According to Cioppa and Lucas [2007], the goal of using a space covering design, such as a Latin hypercube (LH) design, is to reduce large numbers of input variables to fit common, main-effect models that are uncorrelated yet flexible enough to fit complex models. Cioppa and Lucas [2007] expound on orthogonal Latin hypercubes (OLH) by relaxing the orthogonality constraint to expand the number of factors and improve the algorithm to sample further scattered points. Orthogonal designs are commonly used because the estimates will be uncorrelated. Cioppa and Lucas [2007] define a design as nearly orthogonal with a "maximum pairwise correlation no greater than .03 and a condition number no greater than 1.13." Cioppa and Lucas [2007]

found that designs within these thresholds have very minor collinearity and increased space-filling capacity. Comparing nearly orthogonal Latin hypercubes (NOLH) and OLH, NOLH have better space-filling properties and can thus examine many more factors than OLH. "Thus we desire readily available designs that allow analysts to explore how well a diverse set of meta-models captures the relationships between many input variables of a simulation and one or more output variables. Toward that end, we have presented an algorithm that generate NOLH with good space-filling properties. These designs allow an analyst to examine many factors by fitting models with main, quadratic, and interaction effects with nearly uncorrelated estimates of the regression coefficients for the linear effects terms (Cioppa and Lucas [2007])." A space covering design, specifically a NOLH, allows for more factors to be studied while maintaining minimal collinearity.

Ahner and McCarthy [2020] also use a Nearly Orthogonal Latin Hypercube (NOLH) to reduce the vast amount of trials needed for their model, but also to account for as much variability as possible. To cover all possibilities, the minimum and maximum for each input variables was carefully selected to determine the correct range. Ahner and McCarthy [2020] use the NOLH in order to account for the full range of each variable while maintaining limited correlation. This also allows for a reduced number of runs while providing increased information.

Karaoglan et al. [2020] use a response surface method (RSM) to calculate levels of optimum values of flux distribution in permanent magnet generators. They use RSM to build analytical models since RSM is faster and eliminates the trial and error of other popular methods in their field. The RSM also found better results than these other methods.

Hillman [2013] first uses linear regression and the resulting output to build response surfaces. These surfaces were inspected for curvature and significance to com-

pare I-optimal and D-optimal designs. He also found that using RSM improves test efficiency while decreasing the number of trials needed.

As seen in the space covering designs, this method can be applied to find improved results while decreasing the number of runs needed. Similarly, response surface methods offer greater efficiency than other methods that can be used for the same purpose.

III. Methodology

This chapter explains the methodology used to further the development of the simulation tool ENIGMA. The first section addresses the data received from LCOM. The next section discusses fitting response surface models to the LCOM data to create prediction expressions for mean-time-to-repair (MTTR). This section also includes the response surface model analysis. The third section is directed towards implementing the MTTR functions into ENIGMA as well as the creation of other ENIGMA processes. The final sections describes the scenarios developed and run in ENIGMA to determine the relationship between maintenance personnel and sortie generation.

A diagram of the current ENIGMA model is shown in Figure 4 and is originally from Choo [2020]. The inputs required are missions, major events, mean-time-between-failure (MTBF) and MTTR. The missions input requires type and quantity of aircraft to include base or location and current MC status. It also requires scheduled sorties, sortie duration, and departure and return location for each sortie. Major events are any circumstances changing an input. For example, a major event can be used to permanently destroy aircraft by percentage, fixed number, or randomly. The MTTR and MTBF can also be adjusted using a major event. The MTBF is calculated from an exponential distribution. The required input MTBF is the mean of that distribution. MTTR is currently not calculated and is only estimated using LCOM outputs. The remainder of this chapter discusses the implementation of calculating MTTR inside ENIGMA. Other various maintenance repair rates and data can also be input, (e.g., percentage of failures that are engine failures, number of spares available, and time to repair a spare).

As mentioned previously, this work builds off of Choo [2020] by calculating an MTTR using the number of maintenance personnel by AFSC inside the ENIGMA

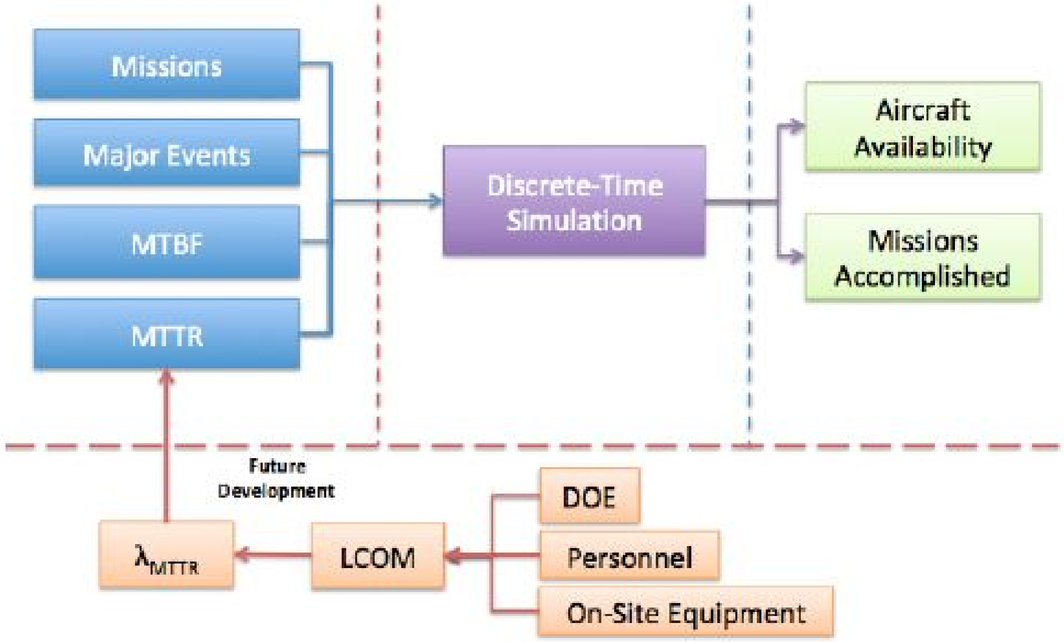


Figure 4. Current ENIGMA Diagram

model. The new ENIGMA diagram can be seen in Figure 5. The biggest difference is LCOM and its required inputs are removed, and replaced by number of available maintenance personnel.

For a detailed description of how ENIGMA works, it is recommended to read Choo [2020]. This thesis focuses on the development of determining an MTTR from the number of maintenance personnel by AFSC and implementing it into ENIGMA, and not the intricacies of ENIGMA itself.

A summary of the methodology used is shown in Figure 6. The process begins with receiving data from LCOM, steps through the response surface modeling process, and ends with the implementation of the MTTR functions into ENIGMA and the development of four scenarios.

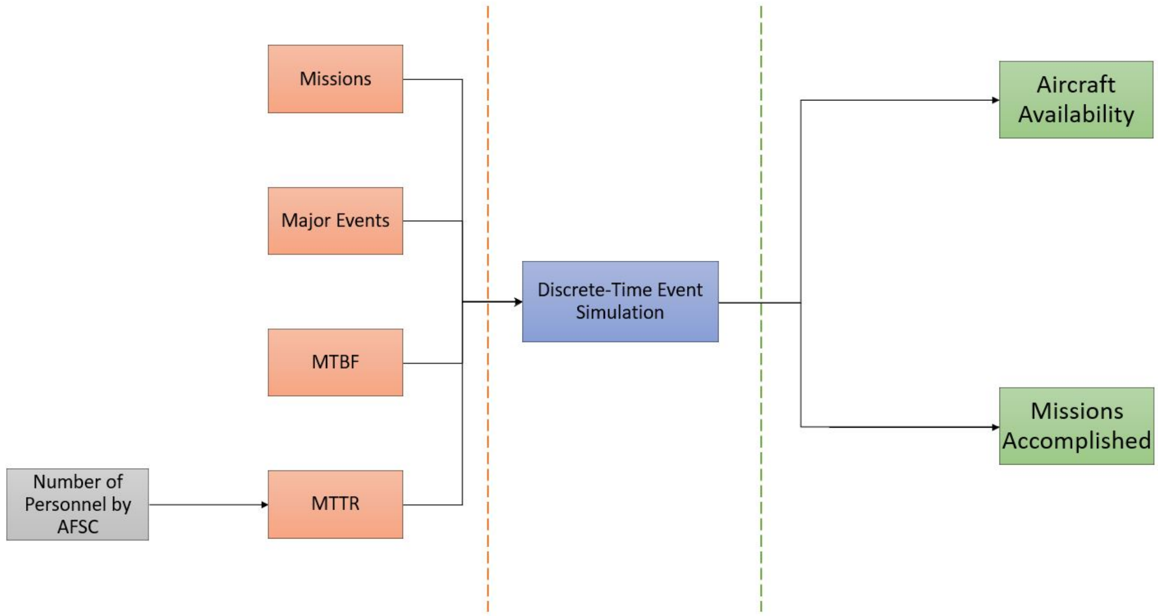


Figure 5. New ENIGMA Diagram

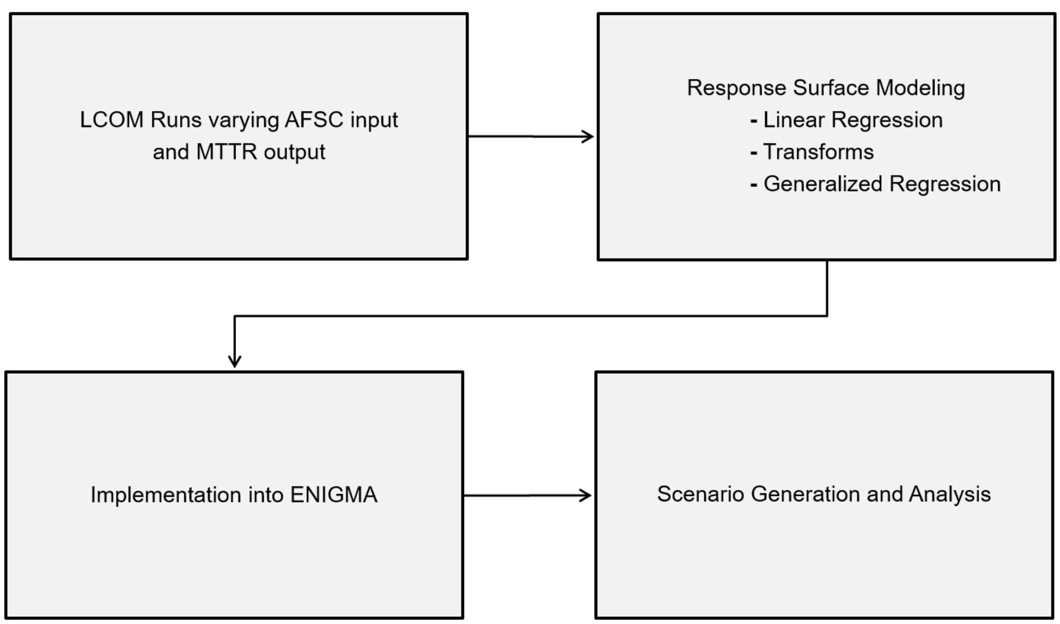


Figure 6. Methodology Overview

3.1 Logistics Composite Model Data

As discussed in section 2.2, LCOM is used to determine manpower requirements for maintenance personnel across the Air Force. This is done by determining the minimum number of personnel required to meet certain sortie rates (Boyle [1990]). LCOM is not limited to solely outputting numbers of personnel required. It also includes metrics associated with the number of personnel and what rates that manning level is able to achieve. This allows for each grouping of personnel to have an associated mean-time-to repair (MTTR). For each airframe, all AFSC's have a number of personnel and associated MTTR. The MTTR varies depending on the number of personnel in each AFSC. Table 2 shows the Airframe, provided AFSC's and associated MTTR. N4 is the MTTR with logistic delays and N5 is the MTTR without logistic delays. These logistic delays are unknown delays in LCOM, thus N5 is used when possible.

Table 2. LCOM Data Summary

Airframe	Air Force Specialty Codes	Mean Time To Repair	Number of Runs
B-2	2A0S1, 2A5A3, 2A5B3, 2A5C3, 2A5P1, 2A5R1, 2A5W1, 2A5X1, 2A6S1, 2A6S3, 2A6S4, 2A6S5, 2A6S6, 2A6T1, 2A6T3, 2A6T6, 2A6X1, 2A6X5, 2A6X6, 2A7C3, 2A7S1, 2A7S2, 2A7S3, 2A7S4, 2A7T3, 2A9L1	N4	260
C-130J	2A5F1, 2A5R1, 2A5W1, 2A6F1, 2A6F5, 2A6F6, 2A6S1, 2A6S4, 2A6S5, 2A6S6, 2A7S1, 2A7S2, 2A7S3, 2A8F1, 2A8F2, 2P5I1, 2P5R1, 2P6S1, 2P6S4, 2P6S5, 2P6S6, 2P7S1, 2P7S2, 2P7S3, 2P8F1, 2P8F2	N4, N5	260
F-15E	2A3X3, 2A3X4B, 2A6X1, 2A6X6, 2W1L1, 2W1X1, 2A0X1S, 2A0T1, 2A3P3, 2A3R3, 2A3W3, 2A6M1, 2A6SG, 2A6S1, 2A6T1, 2A6S3, 2A6S4, 2A6S5, 2A6S6, 2A7S1, 2A7S2, 2A7X3, 2W1S1	N4, N5	261
F-16C	2A0X1K, 2A0X1P, 2A3P3, 2A3W3, 2A3X3, 2A3X4, 2A6A1, 2A6S1, 2A6S6, 2A6T1, 2A6X1, 2A6X3, 2A6X4, 2A6X5, 2A6X6, 2A7X1, 2A7X2, 2A7X3, 2W1L1, 2W1S1, 2W1X1	N4, N5	133
KC-46A	2A5X1, 2A5X3A, 2A5X3B, 2A5X3C, 2A6X1, 2A6X4, 2A6X5, 2A6X6, 2A7X1, 2A7X3	N4	36

3.2 Regression Modeling

Figure 7 shows the process used to generate response surface models. Each step is described in detail.

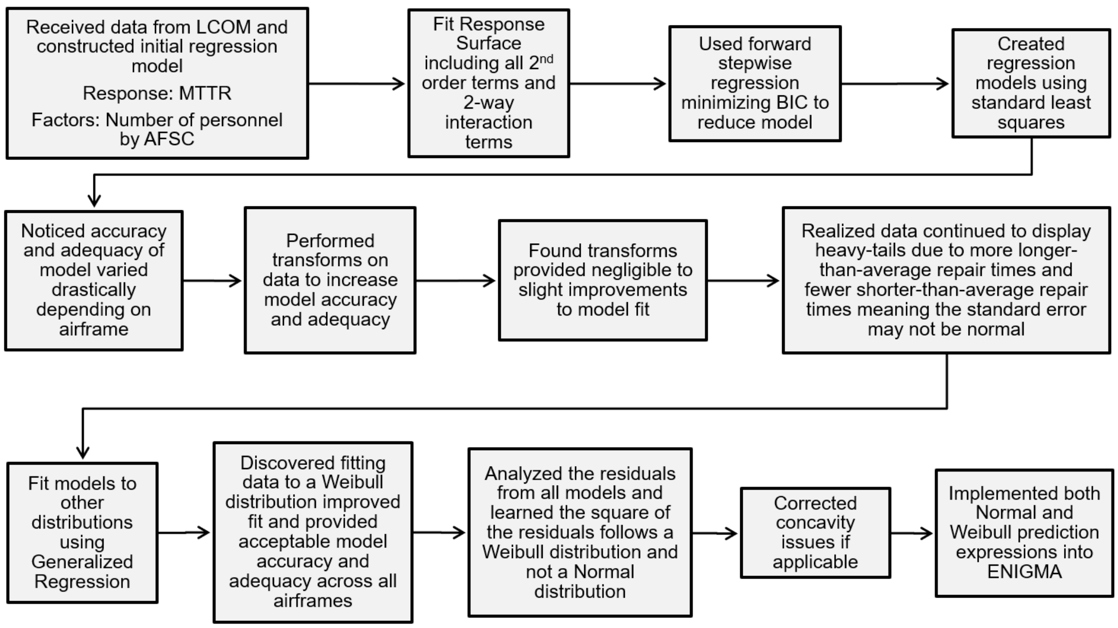


Figure 7. Response Surface Modeling Steps

The data provided from LCOM allowed the AFSCs to be used as regressors and the MTTR to be used as the response. This provided a function of AFSCs to predict MTTR. JMP 15 Pro was utilized to build response surface models for each aircraft. For each aircraft, all AFSCs were added as regressors using the macro "Response Surface". This not only fit a response surface model, but also included all second-order and two-way interaction terms. Employing forward stepwise regression minimizing the Bayesian Information Criterion (BIC), the least significant regressors were eliminated to create a parsimonious model. The significant variables were fit to a model using standard least squares. This method provided very accurate results for the C-130J and KC-46A, acceptable results for the F-16C, and poor results for the F-15E

and B-2. Residual analysis showed that for the poor fitting models, the normality assumption was not being met due to skewed normality plots. This skew caused the normality assumption of regression not to be met. To try and rectify this, transforms were applied and are discussed in the next section.

Table 3 shows the significant variables for the regression models for each aircraft. The number of parameters varies from only two in the B-2 models to 30 in the F-16 models. There also appears to be no similarities between the F-15 and F-16 which are both fighter aircraft with similar maintenance personnel.

3.2.1 Transforms

The results from standard least squares regression are not accurate for all aircraft and there are also signs of the assumptions of regression not being met. The five assumptions of regression are:

1.) Linearity

2.) Constant Variance

3.) Normality of residual errors

4.) No auto-correlation

5.) No multicollinearity

Transforms were applied to the data since some of these assumptions were not being met, specifically linearity and normality. Again utilizing the tools available in JMP 15 Pro, additional models were built using the transform macros on the response variable, MTTR. The transforms applied were log, square-root, square, reciprocal, Box-Cox, and exponential as well as cube-root and cube. These models were fit using the same process as described above. The results from these models offered

Table 3. Significant Variables for Each Aircraft

B-2	C-130	F-15	F-16	KC-46
2A0S1*2A0S1	2A5F1	2A3X4B*2A7S2	2A6X6	2A5X1
2A0S1	2A5F1*2A5F1	2A7S1*2A7X3	2W1S1	2A5X1*2A5X1
	2A6F1	2A7S1*2A7S2	2A3X4*2A3X4	2A5X3C
	2A6F6	2A7X3	2A0X1K*2A7X3	2A6X5
	2A6F1*2A6F1	2A3X4B*2A3W3	2A7X1*2A7X1	2A5X3B*2A5X3C
	2A6F6*2A6F6	2A6T1*2A7S1	2A6X5	2A5X1*2A5X3B
	2A8F2	2A0X1S*2A0X1S	2A7X3*2W1S1	2A5X3A*2A5X3C
	2A8F1*2A8F1	2A6T1*2A6T1	2A3X4*2A6X1	2A5X3A*2A6X5
	2A8F1	2A7S1*2A7S1	2A3P3	2A7X1
	2A8F2*2A8F2	2A7S1	2A6S6*2A6S6	2A6X6
	2A6F5	2A3X3*2A3W3	2A6X6*2A7X3	2A6X5*2A6X6
	2A5F1*2A6F6	2A3X4B	2A6X5*2A7X3	2A5X3A
	2A5R1	2A6T1*2A6S6	2A3X4	2A5X3B
	2P6S4	2A6S6	2A6X1	
		2A3W3	2A6X1*2A6X1	
		2A6T1	2A3X4*2A6X6	
		2A7S2	2A3X4*2A6X4	
		2A3X3	2A6S6	
		2A0X1S	2A7X1	
			2A3P3*2W1X1	
			2A3X3	
			2A3X4*2W1X1	
			2W1L1	
			2A7X3	
			2A6X4	
			2W1L1*2W1L1	
			2A3X3*2A6X1	
			2A0X1K	
			2W1X1	
			2A6S6*2W1X1	

no significant improvement regarding model accuracy and adequacy. The transforms provided worse, no change, or slightly improved results. Although some results were slightly better, they were not significantly improved enough to select the transformed model over the current model. Residual analysis of these transformed models continued to show non-normality of the errors. Further analysis also continued to prove that there were more longer-than-average repair times than shorter-than-average repair times. In other words, repair times are likelier to take longer than average, rather than shorter than average. This caused belief that the standard error is not normally distributed and other statistical distributions should be investigated.

3.2.2 Generalized Regression

Due to the non-normal standard error, additional models were fit using generalized regression. Following the same process as in section 3.2, instead of using standard least squares with a normal distribution to build the model, generalized least squares was used with Weibull, gamma, and lognormal distributions. The gamma and lognormal models provided no to negligible improvements. The Weibull models all provided improved models for all airframes as seen in Table 4. The F-15E and B-2 models offered acceptable accuracy and adequacy and the other models accounted for more variance than the previous models.

3.2.3 Residual Analysis

Analyzing the residuals from these models, it was discovered the studentized residuals follow a Weibull distribution and not a normal distribution. This verified the use of generalized regression fit to a Weibull distribution. Comparing the Weibull and normal distributions found that the average predicted MTTR is very similar, but the models assuming a normal distribution for the errors have a larger variance than the

Weibull models. Table 4 displays details and a comparison of each of the regression models for each aircraft. It can be seen that when using maximum likelihood fit to a Weibull distribution, the R-squared value is equal to or better than standard least squares as seen in Table 4. The R-squared value is used because an adjusted R-squared cannot be determined for the Weibull models. The Weibull models also have a lower AICc and BIC, indicating these models are a better fit than the normal models. The number of parameters in each model can also be seen and a detailed list can be found in Table 3.

Most importantly, from these models, a prediction expression for MTTR was generated from the LCOM experiments. Table 5 shows the equation number for each prediction expression by airframe and distribution. These equations can be found in Appendix A.

These LCOM-derived models were validated by analyzing MTTR versus maintenance manning levels. As maintenance personnel increase, the MTTR should decrease exponentially. This was the case for all aircraft except the F-15. For the F-15, increasing maintenance personnel past the median level results in a significant increase in MTTR. To counter this, when the F-15 manning level passes median, the F-15 personnel are broken into two separate maintenance teams, each with its own MTTR. This avoids a convex function for F-15 MTTR, and replaces it with an exponential decay function.

The equations from these models allow an MTTR to be calculated based on the number of personnel by AFSC for each aircraft. This is important because now LCOM does not have to be run each time to calculate an MC rate or ideal flying schedule. Implementing these equations into ENIGMA will produce similar results in a much faster, easier to use format. Both the standard least squares models and generalized regression Weibull models are implemented into ENIGMA. The two different functions

Table 4. Regression Model Comparison

Aircraft	Distribution	Estimation Method	Nonzero Parameters	μ	σ	α (scale)	β (shape)	AICc	BIC	Adjusted R-Square	R-square
B-2	Weibull	Maximum Likelihood	4	2.787	0.137	16.234	7.295	1222.633	1236.719	–	0.77
	Normal	Standard Least Squares	4	16.019	3.587	–	–	1407.21	1421.296	0.51	0.51
C-130	Weibull	Maximum Likelihood	16	2.792	0.066	16.321	15.260	854.373	909.105	–	0.92
	Normal	Standard Least Squares	16	16.314	1.300			892.9688	947.701	0.90	0.90
F-15	Weibull	Maximum Likelihood	21	1.065	0.016	2.900	61.440	-750.793	-680.096	–	0.80
	Normal	Standard Least Squares	21	2.902	0.049	–	–	-797.621	-726.925	0.43	0.47
F-16	Weibull	Maximum Likelihood	32	1.244	0.032	3.470	31.651	-78.553	-10.007	–	0.88
	Normal	Standard Least Squares	32	3.463	0.151	–	–	-68.624	-0.0781	0.70	0.77
KC-46	Weibull	Maximum Likelihood	15	2.947	0.009	19.043	114.210	43.576	43.329	–	0.99
	Normal	Standard Least Squares	15	19.034	0.321	–	–	56.6025	56.355	0.98	0.99

Table 5. Prediction Expression Reference

Airframe	Distribution	Equation Number
B-2	Weibull	8
	Normal	9
C-130	Weibull	10
	Normal	11
F-15	Weibull	12
	Normal	13
F-16	Weibull	14
	Normal	15
KC-46	Weibull	16
	Normal	17

will be compared to determine if there is a true difference in results.

3.3 Implementation into ENIGMA

The prediction expressions from each of the regression models for each aircraft are implemented into ENIGMA. Two different functions are created, one normal and one Weibull prediction expression for each aircraft. The function that assumes the residual errors follow a normal distribution is called the normal function, while the function that assumes the residual errors follow a Weibull distribution is called the Weibull function. Each function reads the AFSC codes and values from an input spreadsheet (see Table 6). The number of personnel for each AFSC is then assigned to a variable with the same AFSC code. These variables go through an error checking process to ensure the number of personnel for each AFSC is within the limits of the data provided by LCOM. If the value is less than the minimum or greater than the maximum, an error message is output stopping the function. If all the variables are within proper limits, the variables are substituted into the MTTR equation which is solved, and an MTTR is output. This output MTTR is checked again by the function to ensure the output MTTR is not zero or empty. After passing all checks, this MTTR is defined as a new variable and stored to be used by ENIGMA for the specified aircraft.

The MTTR functions are nested within another function which converts the input files to input data that can be used by ENIGMA. This function first determines which aircraft and bases are in the model, then for each airframe at each base, this outer function calls the corresponding MTTR function based upon the distribution chosen (Normal or Weibull). An MTTR is calculated for each aircraft at each base using the provided personnel values. The output MTTR is stored in a struct with other maintenance data to reference when needed.

Similarly, a function to determine the number of aircraft that can be worked on simultaneously was also created. This function was determined by the AFSC with

the lowest minimum number of personnel. This AFSC was chosen because if multiple aircraft break it may be for the same problem requiring that specific AFSC. Assuming each broken aircraft requires at least one person with that AFSC, the number of personnel with that AFSC becomes how many aircraft can be worked at one time. However, this number of simultaneously worked aircraft must be adjusted when more than the minimum personnel are available. Since the AFSC values differ for each aircraft, this function also differs for each aircraft. To ensure the final output is an integer number, some equations use rounding. These equations can be seen below. Note, $NumSim$ represents the number of simultaneous worked aircraft.

B-2 Number of Aircraft able to be worked simultaneously:

$$NumSim = round((2A0S1/4) + 0.5) \tag{3}$$

C-130 Number of Aircraft able to be worked simultaneously:

$$NumSim = round(2 * 2A6F5/3) \tag{4}$$

F-15 Number of Aircraft able to be worked simultaneously:

$$NumSim = 2A6T1 \tag{5}$$

F-16 Number of Aircraft able to be worked simultaneously:

$$NumSim = 2A6X5 \tag{6}$$

KC-46 Number of Aircraft able to be worked simultaneously:

$$NumSim = round(2A6X6/4) \tag{7}$$

These functions have similar error checking as the MTTR function. It first reads the input AFSC file to find the needed AFSC, ensures it is within proper limits, computes the number of aircraft, and checks to make sure it is not zero or empty. Once passing these checks, this number is used by the model. These *NumSim* functions are also nested within the same function as the MTTR functions and are used in the same manner. Since the number of aircraft able to be worked simultaneously is dependent on AFSC values, each time the MTTR functions are called, the function for number of simultaneous aircraft worked is also called to ensure this value is correct and has not changed.

In order for these functions to work, AFSC codes and their manning levels are required inputs. These inputs are read in from an Excel spreadsheet. One spreadsheet is required for each airframe. The first column contains the AFSC codes, and the second and sequential columns contain the number of personnel with that AFSC code at each base, where each column represents a base. An example can be seen in Table 6.

Table 6. Example Input AFSC File for C-130 at two bases

AFSC	Base A	Base B
2A5F1	48	4
2A5R1	9	4
2A6F1	16	3
2A6F5	6	3
2A6F6	13	2
2A8F1	13	3
2A8F2	9	2
2P6S4	6	3

These AFSC spreadsheets are loaded via the ENIGMA GUI before the simulation is run. The GUI was also updated to allow for the loading, clearing, viewing, and editing of the input AFSC files. A selection switch was added to the GUI to select the Normal or Weibull functions. If "Normal" is selected the model will use the normal

functions, and if “Weibull” is selected the model will use the Weibull functions. The AFSC files are loaded using the already existing function “getFile” used to load the other required input files. This function is able to read the file and convert the data into a cell array that can be used by the model. This function also checks for any missing values in the input data. The data is also able to be displayed as a table in the GUI. The AFSC files are able to be edited using the already existing GUI controls.

Lastly, two major events were added to adjust the manning levels during a run. These were added under the “perform Major Events” function in ENIGMA. The first major event attrits the manning level by a percentage specified by the user. The second major event allows the user to load a new AFSC file with a different manning level. These major events are executed by using the Major Events input file. In the Major Events input file, the day of event, type of aircraft and base are specified along with the desired even, in this case, “Attrit AFSC” or “Load New AFSC”. A value for Attrit AFSC is required in the “Event Data” column. This value must be greater than zero and less than one as it is the percentage of personnel remaining. For example, to reduce the personnel by 10%, 0.9 would added in the last column. The function for this event determines which day, which airframe, and which base the personnel are being attrited. The event data value is multiplied by the current AFSC levels and rounded to the nearest integer. This major event function does not allow the minimum number of personnel to be bypassed. If the number of personnel is attrited below the minimum, the minimum value for that AFSC is used. The new AFSC levels are passed into the MTTR and number simultaneous functions and a new MTTR and number of simultaneously worked aircraft are calculated. When choosing to load a new AFSC file, a command window opens, asking for the new file to be selected. The new file is read in and input into the MTTR and number simultaneous

functions to calculate the new MTTR and number of simultaneously worked aircraft.

Table 7 shows the major events used and a description of what each major event does.

Table 7. Description of Major Events Used

Major Event	Function
Load New AFSC	Allows new AFSC file to be loaded for defined base and aircraft
Attrit AFSC	Reduces current manning by defined percentage
Destroy Fixed Number Specific Aircraft	Destroys the defined number and type of aircraft
Destroy Fixed Number Aircraft	Randomly destroys the defined number of aircraft

The final ENIGMA model allows for manning levels to be loaded, a distribution selected to determine which function to use, and an MTTR and number of simultaneously worked aircraft to be calculated. Two different major events can be applied to alter the manning levels during a run.

3.4 Scenario Development

Four scenarios are developed as baselines to provide important insights and to demonstrate the capabilities of ENIGMA. Factors changed during the scenarios include number of personnel, number of aircraft, and number of sorties. Each of the scenarios will be discussed in detail along with the excursions that illustrate the effectiveness of ENIGMA and provide even further insights. Each scenario lasts 50 days and 100 replications were performed.

3.4.1 Scenario 1

Scenario 1 addresses the effects of maintenance personnel build up. It is based on a unit deploying and accounts for the increase of maintenance personnel to a base with all aircraft present the entire scenario. Table 8 shows the details of Scenario 1 with the differences in maintenance personnel between the baseline and excursions given in Table 9. This scenario has a single base with 24 F-15's, 24 F-16's, 8 B-2's, 8 C-130's,

and 8 KC-46's. The fighter aircraft each fly 20 sorties lasting 4 hours each day while the remaining non-fighter aircraft fly 6 sorties each for a duration of 6 hours. The attrition rate for all aircraft is the same at 0.001%. There are two types of failures for each airframe. Engine failures account for 10% of the failures. Fighters have 3 spare engines while non-fighters have 2 spare engines. The time to repair an engine is 12 days for all aircraft. All other failures account for the remaining 90% of failures with zero spares on hand. The time to replace any type of spare is 1 day for all aircraft. As previously discussed, the MTTR and Maximum Number of Simultaneous Repairs is determined by the AFSC levels. The MTBF is 24 hours and 36 hours for fighters and non-fighters respectively. The major events used in this scenario are "Load New AFSC" and "Attrit AFSC", described in Table 7.

Table 9 compares the baseline and excursions for scenario one. The baseline uses maximum personnel for the entirety of the 50 day scenario. Each excursion begins with minimum personnel and has increasing personnel over different rates. Excursion 1 begins with minimum personnel which increases to median personnel on day 5 and reaches maximum personnel at day 10. Excursion 2 also begins with minimum personnel, but increases by 20% of maximum personnel on day 5, increases by 50% of maximum personnel on day 10 and reaches maximum personnel on day 15. Excursion 3 again begins with minimum personnel, increase to the 25th percentile of personnel on day 5, median personnel on day 10, 75th percentile on day 15 and maximum personnel on day 20. Each excursion adds an additional 5 days before the maximum manning level is reached.

Table 8. Scenario 1: Properties

Property	Value Fighters (F-15, F-16)	Value Others (B-2, C-130, KC-46)
Number of Aircraft at this Base	24	8
Number of Single Aircraft Missions Each Day	20	6
Duration of Each Mission	4 hours	6 hours
Attrition Rate of Each Mission	0.001	0.001
Types of Failures	Engine: - Proportion of Failures: 0.1 - Number of Spares: 3 -Time to replace Spare: 12 Days Other: - Proportion of Failures 0.9 - Number of Spares: 0 - Time to replace Spare: 1 Days	Engine: - Proportion of Failures: 0.1 - Number of Spares: 2 -Time to replace Spare: 12 Days Other: - Proportion of Failures 0.9 - Number of Spares: 0 - Time to replace Spare: 1 Days
MTTR	Function of AFSCs	Function of AFSCs
Maximum Number of Simultaneous Repairs	Function of AFSCs	Function of AFSCs
MTBF	24 hours	36 hours
Major Events	Load New AFSC	Load New AFSC

Table 9. Scenario 1: Baseline and Excursion Comparison

Day of Event	Baseline	Excursion 1	Excursion 2	Excursion 3
0	Max Personnel	Min Personnel	Min Personnel	Min Personnel
5		Median	Min + 0.2*Max	25th pctl
10		Max	Min + 0.5*Max	Median
15			Max	75th pctl
20				Max

3.4.2 Scenario 2

Scenario 2 is base consolidation. The idea for this scenario is that there are two bases and half of one base is destroyed. This scenario then explores the options of operating at both bases with one base operating at 50% or consolidating to a single base operating at increased capacity. Table 10, Table 11, and Table 12 show the details of Scenario 2.

This scenario models 2 bases, base 1 and base 2. The number of aircraft at each base and number of sorties flown each day differs and will be discussed during the baseline versus excursions. The duration for each sortie is 4 hours and 6 hours for fighters and non-fighters respectively. The attrition rate remains at 0.001%. Engine failures account for 10% of failures with 3 spares for fighters and 2 spares for non-fighters. The time to replace a spare engine is 12 days for both. Other failures account for the remaining 90% of failures with zero spares on hand and one day to replace a spare. The MTBF is 24 hours for fighters and 36 hours for non-fighters. The major events used are "Destroy Fixed Number Specific Aircraft" and "Load New AFSC". Descriptions of these events are in Table 7.

Table 11 and Table 12 compare the manning and aircraft levels across the baseline and excursions for scenario 2. The baseline has a median manning level for the entire duration of the scenario with 24 of each fighter aircraft and 8 of each non-fighter aircraft with no changes during the simulation. Excursion 1 begins with median manning levels at each base and 24 of each fighter aircraft and 8 of each non-fighter aircraft at each base. On day 10, the manning at base 1 is reduced by half to the 25th percentile manning level and aircraft at base 1 are also reduced by half to 12 fighters and 4 non-fighters. Excursion 2 begins the same as excursion 1, but instead of base 1 operating at 50% capacity, the personnel and aircraft are moved to base 2. So now on day 10, there are no personnel or aircraft at base 1, and base 2 has 75th

percentile manning with 36 of each fighter aircraft and 12 of each non-fighter aircraft. Table 10 notation for aircraft and sorties is Base 1/Base 2 and Baseline → Excursion 1 → Excursion 2.

Table 10. Scenario 2: Properties

Property	Value Fighters (F-15, F-16)	Value Others (B-2, C-130, KC-46)
Number of Aircraft at this Base	24/24 → 12/24 → 0/36	8/8 → 4/8 → 0/12
Number of Single Aircraft Missions Each Day	20/20 → 10/20 → 0/30	6/6 → 3/6 → 0/9
Duration of Each Mission	4 hours	6 hours
Attrition Rate of Each Mission	0.001	0.001
Types of Failures	Engine: - Proportion of Failures: 0.1 - Number of Spares: 3 -Time to replace Spare: 12 Days Other: - Proportion of Failures 0.9 - Number of Spares: 0 - Time to replace Spare: 1 Days	Engine: - Proportion of Failures: 0.1 - Number of Spares: 2 -Time to replace Spare: 12 Days Other: - Proportion of Failures 0.9 - Number of Spares: 0 - Time to replace Spare: 1 Days
MTTR	Function of AFSCs	Function of AFSCs
Maximum Number of Simultaneous Repairs	Function of AFSCs	Function of AFSCs
MTBF	24 hours	36 hours
Major Events	Destroy Fixed Number Specific Aircraft Attrit AFSC	Destroy Fixed Number Specific Aircraft Attrit AFSC

Table 11. Scenario 2: Baseline and Excursion Maintenance Personnel Comparison

Day of Event	Baseline		Excursion 1		Excursion 2	
	Base 1	Base 2	Base 1	Base 2	Base 1	Base 2
0	Median	Median	Median	Median	Median	Median
10			25th pctl	Median	None	75th pctl

Table 12. Scenario 2: Baseline and Excursion Aircraft Comparison

Day of Event	Baseline (Fighter/Non-fighter)		Excursion 1 (Fighter/Non-fighter)		Excursion 2 (Fighter/Non-fighter)	
	Base 1	Base 2	Base 1	Base 2	Base 1	Base 2
0	24/8	24/8	24/8	24/8	24/8	24/8
10			12/4	24/8	0/0	36/12

3.4.3 Scenario 3

Scenario 3 models attrition. Both personnel and aircraft are attrited. This scenario represents a continuous high-casualty situation or location, studying the effects

of losing both aircraft and personnel. Table 13 and Table 14 show the details of Scenario 3.

For scenario 3, the number of aircraft decreases every 10 days. Fighter aircraft begin with 24, are randomly reduced every 10 days. Similarly, non-fighter aircraft are also randomly reduced every 10 days. The number of sorties scheduled is adjusted to account for the loss of aircraft. Fighter aircraft start by flying 20 sorties each day and this is reduced every 10 days to 15, 12, 9, and 7. Non-fighter aircraft start by flying 6 sorties, and this is reduced to 4, 3, 2 (and remains at 2) every 10 days. The duration of each sortie remains at 4 hours and 6 hours for fighter and non-fighter aircraft respectively. Types of failures and MTBF also remain the same as the previous scenarios. The major events used are "Destroy Fixed Number Aircraft", "Load New AFSC", and "Attrit AFSC".

The baseline for this scenario uses the maximum number of personnel for the entire scenario. Excursion 1 decreases the number of personnel to the 75th percentile on day 10, median on day 20, 25th percentile on day 30 and minimum on day 40. Excursion 2 attrits the number of personnel by 10% every 5 days and excursion 3 attrits the number of personnel by 20% every 5 days.

Table 13. Scenario 3: Properties

Property	Value Fighters (F-15, F-16)	Value Others (B-2, C-130, KC-46)
Number of Aircraft at this Base	24 (randomly decreased)	8 (randomly decreased)
Number of Single Aircraft Missions Each Day	$20 \rightarrow 15 \rightarrow 12 \rightarrow 9 \rightarrow 7$	$6 \rightarrow 4 \rightarrow 3 \rightarrow 2 \rightarrow 2$
Duration of Each Mission	4 hours	6 hours
Attrition Rate of Each Mission	0.001	0.001
Types of Failures	Engine: - Proportion of Failures: 0.1 - Number of Spares: 3 -Time to replace Spare: 12 Days Other: - Proportion of Failures 0.9 - Number of Spares: 0 - Time to replace Spare: 1 Days	Engine: - Proportion of Failures: 0.1 - Number of Spares: 2 -Time to replace Spare: 12 Days Other: - Proportion of Failures 0.9 - Number of Spares: 0 - Time to replace Spare: 1 Days
MTTR	Function of AFSCs	Function of AFSCs
Maximum Number of Simultaneous Repairs	Function of AFSCs	Function of AFSCs
MTBF	24 hours	36 hours
Major Events	Destroy Fixed Number Aircraft Load New AFSC Attrit AFSC	Destroy Fixed Number Aircraft Load New AFSC Attrit AFSC

Table 14. Scenario 3: Baseline and Excursion Comparison

Day of Event	Aircraft Attrition	Baseline	Excursion 1	Excursion 2	Excursion 3
0	72	Max Personnel	Max Personnel	Max Personnel	Max Personnel
5				Current – 10%	Current – 20%
10	54		75th pctl	Current – 10%	Current – 20%
15				Current – 10%	Current – 20%
20	40		Median	Current – 10%	Current – 20%
25				Current – 10%	Current – 20%
30	31		25th pctl	Current – 10%	Current – 20%
35				Current – 10%	Current – 20%
40	22		Min	Current – 10%	Current – 20%
45				Current – 10%	Current – 20%
50	End	End	End	End	End

3.4.4 Scenario 4

Scenario 4 explores differing ops-tempos. This scenario models swings from high-ops-tempo to low-ops-tempo to see the strain on maintenance personnel and sortie generation. Table 15 and Table 16 show the details of Scenario 4.

Scenario 4 models a single base with 24 F-15's, 24 F-16's, 8 B-2's, 8 C-130's, and 8 KC-46's. The fighter aircraft either fly 30 sorties or 10 sorties a day while non-fighter aircraft fly 9 or 3 sorties per day. The sortie duration for fighters is 4 hours and for non-fighters it is 6 hours. The attrition rate is 0.001%. Engine failures account for 10% of all failures. Fighters have 3 spare engines while non-fighters have 2 spare engines. The time to repair an engine is 12 days for all aircraft. All other failures account for the remaining 90% of failures with zero spares on hand. The time to replace any spare is one day for all aircraft. The MTBF is 24 hours and 36 hours respectively for fighters and non-fighters. No major events were used in this scenario.

The baseline and excursions are compared in Table 16. The number of sorties flown are the same for the baseline and excursions. Thirty sorties are flown for the first 10 days, then 10 sorties for 5 days, 30 sorties for 10 days, 10 sorties for 5 days and so on until 50 days are reached and the scenario ends. Similarly, non-fighter aircraft fly 9 sorties for 10 days and 3 sorties for 5 days alternating until 50 days are reached. The baseline operates with median personnel, excursion 1 with minimum personnel and excursion 2 with maximum personnel.

An additional excursion is added to scenario 4 as previous scenarios did not stress the limits of MTBF and MTTR in the model. To stress these limits, the scheduled sorties are doubled from the scenario 4 baseline. The maintenance personnel level remains the same at median. A comparison of the baseline and new excursion can be seen in Table 17.

In excursion 3, the scheduled sorties are doubled from the baseline. Fighter aircraft

Table 15. Scenario 4: Properties

Property	**Value Fighters (F-15, F-16)**	**Value Others (B-2, C-130, KC-46)**
Number of Aircraft at this Base	24	8
Number of Single Aircraft Missions Each Day	Harder fight: 30 Lesser fight: 10	Harder fight: 9 Lesser fight: 3
Duration of Each Mission	4 hours	6 hours
Attrition Rate of Each Mission	0.001	0.001
Types of Failures	Engine: - Proportion of Failures: 0.1 - Number of Spares: 3 -Time to replace Spare: 12 Days Other: - Proportion of Failures 0.9 - Number of Spares: 0 - Time to replace Spare: 1 Days	Engine: - Proportion of Failures: 0.1 - Number of Spares: 2 -Time to replace Spare: 12 Days Other: - Proportion of Failures 0.9 - Number of Spares: 0 - Time to replace Spare: 1 Days
MTTR	Function of AFSCs	Function of AFSCs
Maximum Number of Simultaneous Repairs	Function of AFSCs	Function of AFSCs
MTBF	24 hours	36 hours
Major Events	None	None

Table 16. Scenario 4: Baseline and Excursion Comparison

Day of Event	Scheduled Sorties (Fighters/Non-fighters)	Baseline	Excursion 1	Excursion 2
0	30/9	Median Personnel	Minimum Personnel	Maximum Personnel
10	10/3			
15	30/9			
25	10/3			
30	30/9			
40	10/3			
45	30/9			
50	10/3			

Table 17. Scenario 4: Baseline versus Excursion 3 Comparison

Day of Event	**Baseline** **Median Personnel**	**Excursion 3** **Median Personnel**
	Sorties (Fighters/Non-fighters)	**Sorties (Fighters/Non-fighters)**
0	30 / 9	60 / 18
10	10 / 3	20 / 6
15	30 / 9	60 / 18
25	10 / 3	20 / 6
30	30 / 9	60 / 18
40	10 / 3	20 / 6
45	30 / 9	60 / 18
50	End	End

alternate between flying 60 sorties for 10 days and 20 sorties for 5 days while non-fighter aircraft alternate between flying 18 sorties for 10 days and 6 sorties for 5 days. This increase in sorties will test the limits of MTTR and maintenance personnel.

The minimum, 25th percentile, median, 75th percentile, and maximum manning levels referenced by the scenarios can be found in Appendix B. After developing these scenarios, all necessary input files were created to run the scenarios. These scenarios were run differently than actual wargaming scenarios. The purpose of these scenarios is academic, to determine the long-run affect of maintenance manning levels on sortie generation. This is why a 50 day simulation is used. Typical wargames are generally much shorter in length, lasting several days to a week. Wargaming simulations are often times only run for a few days and are then stopped to analyze the results to make any necessary changes before continuing the simulation. Performing these scenarios in a true wargame fashion would make it difficult to assess the affect of maintenance personnel on sortie generation.

IV. Results and Analysis

The results and analysis cover three areas within each scenario. First is the comparison between the normal and Weibull MTTR functions, testing whether there is a statistical significant difference between the two functions. To test for a significant difference, a paired t-test for means is performed, hypothesizing there is no difference between means. The α value used is 0.05 thus any two-tail P values below 0.05 signify a statistical significant difference between the normal and Weibull functions. The statistically significant different paired t-test values are highlighted.

Second is the comparison between the baseline and excursions within each scenario. An operational metric is used to compare number of mission-capable aircraft and number of sorties flown. Multiple metrics are able to be used to compare the operational capabilities between excursions. One metric is the area under the curve, for the minimum, average and maximum MC aircraft and sorties flown. Since each day has a width of 1, summing the minimums, averages, and maximums equals the area under the curve. These areas can then be compared, with larger areas equating to better performance since more MC aircraft and more sorties flown are desirable. Similarly, the areas between the minimum and maximum, and average and maximum could be compared. These are found by calculating the difference between the maximum and minimum, and the difference between the maximum and average. In this instance, a smaller area is desirable since non-MC aircraft and sorties not flown are being compared. Another comparison metric is percent of MC aircraft and percent of sorties flown in each excursion. This is found by summing the minimum, average and maximum number of MC aircraft and sorties flown and dividing by the total possible number of MC aircraft and number of scheduled sorties. This last metric is used because by using percentages, the values can be compared across scenarios and airframes with differing numbers of aircraft and scheduled sorties.

Third is a comparison within the scenario by type of aircraft, comparing the operational differences between average number of MC aircraft and average number of sorties flown.

4.1 Scenario 1 Results, Analysis, and Insights

4.1.1 Normal versus Weibull

The model comparison between the different regression models assuming the errors follow a normal distribution and a Weibull distribution is made first, and Table 18 shows the significant difference for MC aircraft for scenario 1. There is no significant difference between the functions when it comes to the maximum number of MC aircraft. There is a significant difference as indicated by the highlighted numbers in Table 18 for average number of MC aircraft for the baseline and excursions 1 and 2, but not excursion 3. And only excursion 2 shows a significant difference for the minimum number of MC aircraft.

Table 18. Scenario 1: Paired T-test *P* Values for Number of MC Aircraft

	Maximum *P Value*	Average *P Value*	Minimum *P Value*
Baseline	0.192	0.008	0.183
Excursion 1	0.498	0.041	0.963
Excursion 2	0.878	0.031	0.000
Excursion 3	0.755	0.945	0.550

Table 19 compares the significant difference for number of sorties flown for scenario 1. The maximum number of sorties flown is unable to be compared since there is no difference in maximum number of sorties flown between the two functions. In all excursions, all sorties were flown for the maximum in both cases. Only excursion 2 shows a significant difference between functions for number of sorties flown for both the average and minimum.

Table 19. Scenario 1: Paired T-test P Values for Number of Sorties Flown

	Maximum P Value	Average P Value	Minimum P Value
Baseline	NA	0.204	0.152
Excursion 1	NA	0.855	0.816
Excursion 2	NA	0.001	0.003
Excursion 3	NA	0.556	0.759

Figure 8 best shows the difference between the normal and Weibull functions for MC aircraft in this scenario for excursion 2. The solid line depicts the Weibull function values while the dashed line represents the normal function values. For this excursion, there is no statistical difference between the maximums. However, there is a statistical difference between the averages and minimums. For the averages, the difference is most evidenced in days 11 to 27, where the normal average is clearly above the Weibull average. For the minimums, the Weibull values appear lower than the normal values from day 23 onward.

Figure 9 shows the difference in number of sorties flown for scenario 1, excursion 2. This is the only excursion for scenario 1 where there is a difference in the average and minimum sorties flown between the two functions. The average difference is most clear days 3 to 13 where the Weibull average is lower than the normal average. The Weibull minimums are also much lower day 22 and onward.

Additional normal versus Weibull plots for the other excursions from this scenario can be found in Appendix D, Figures 30 to 33.

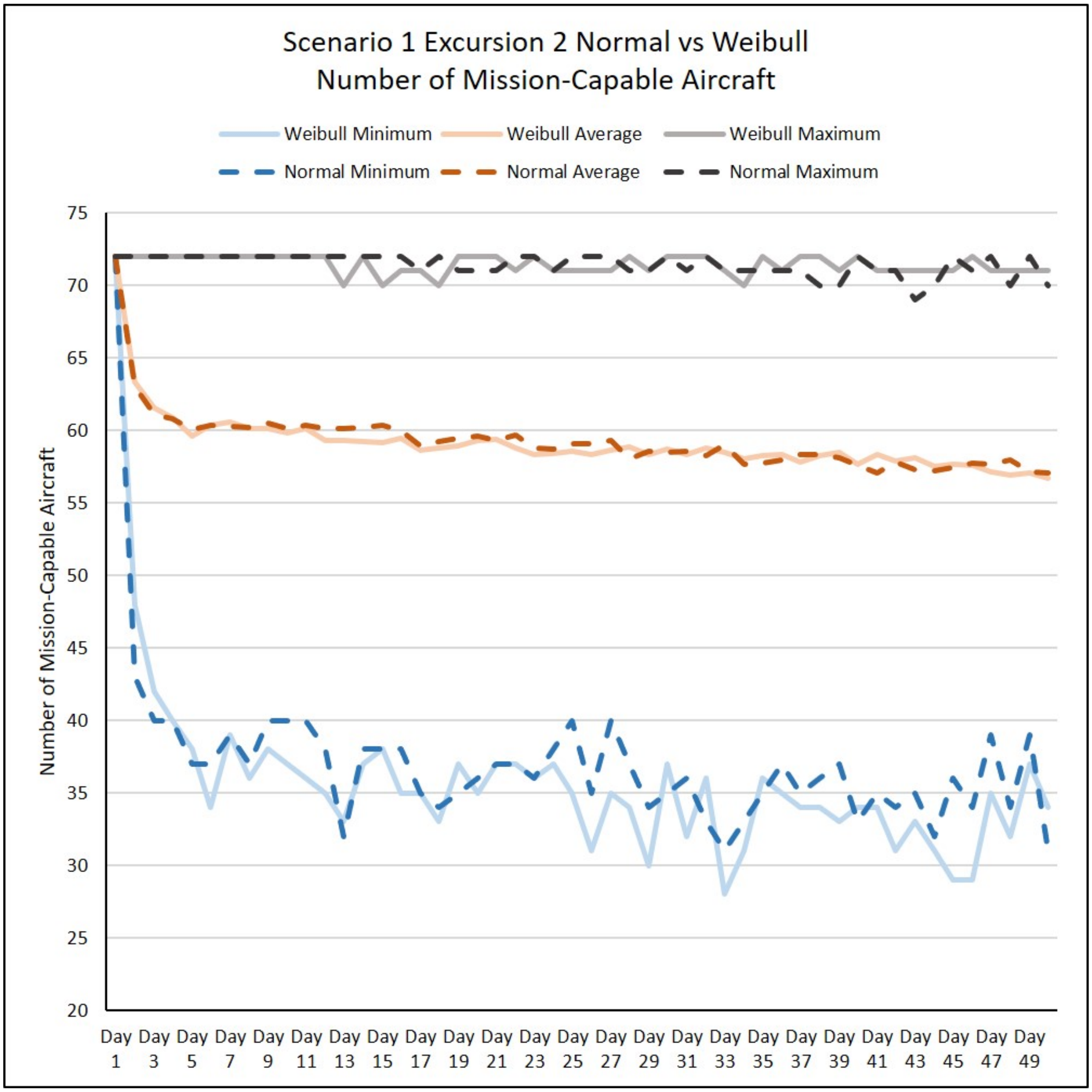


Figure 8. Scenario 1: Excursion 2 Normal versus Weibull Number of MC Aircraft

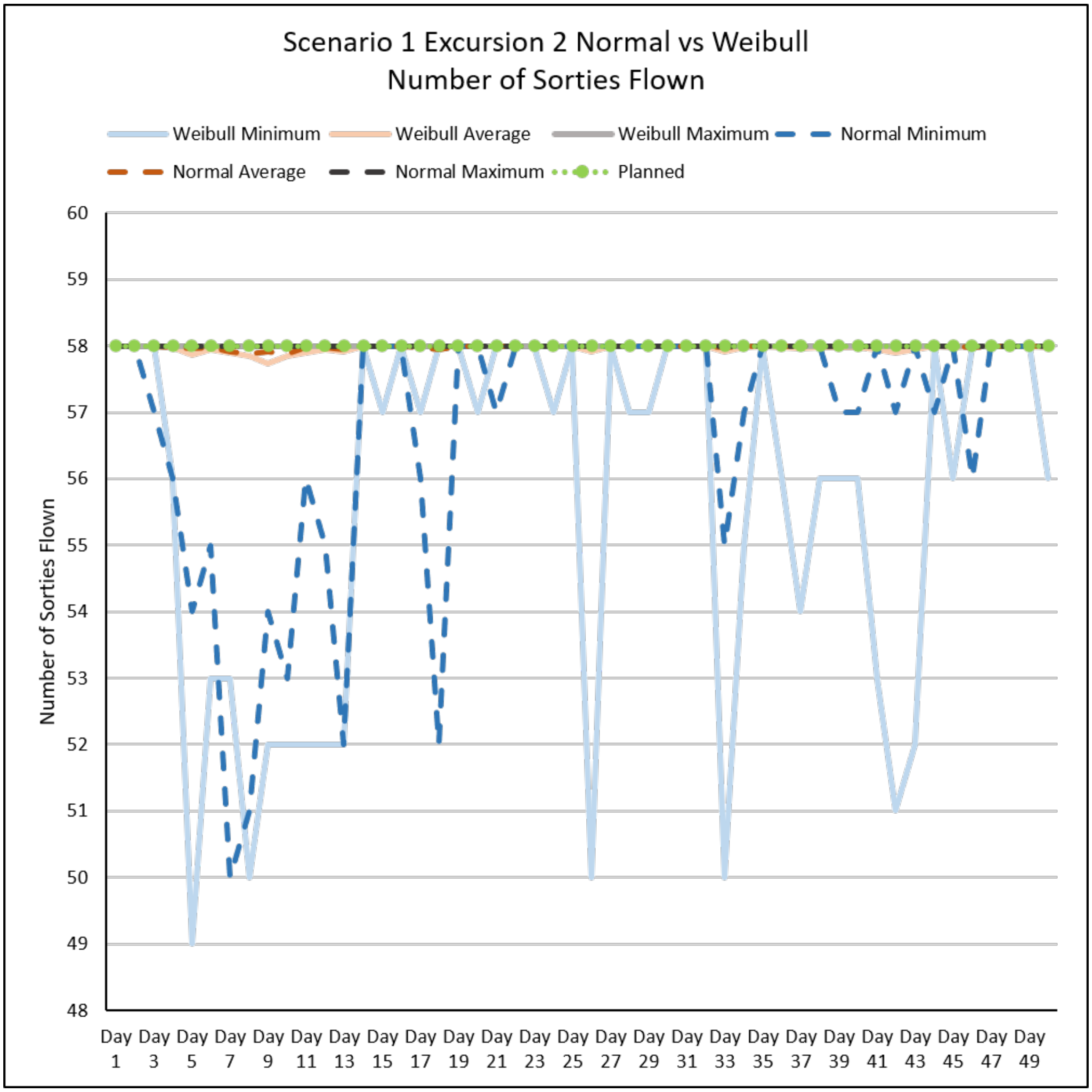


Figure 9. Scenario 1: Excursion 2 Normal versus Weibull Number of Sorties Flown

4.1.2 Baseline versus Excursions

This section compares the scenario 1 baseline to the scenario 1 excursions. Table 20 shows the percent of MC aircraft using the Weibull function. The maximum number of MC aircraft increases 0.2% from the baseline to excursion 3. The average number of MC aircraft decreases 0.2% from the baseline to excursion 3. It is interesting to note the maximum increases as the slower maintenance personnel increases, while the average slightly decreases as the slower maintenance personnel increases. The minimum also increases for excursions 1 and 2, but decreases for excursion 3 showing much more variability.

Table 20. Scenario 1: Percent Mission-Capable Aircraft Weibull

	Maximum Percent MC Aircraft	Average Percent MC Aircraft	Minimum Percent MC Aircraft
Baseline	99.1%	82.2%	49.4%
Excursion 1	99.2%	82.1%	50.9%
Excursion 2	99.2%	82.1%	49.6%
Excursion 3	99.3%	82.0%	49.2%

Table 21 displays the percent of MC aircraft using the normal function for scenario 1. Both the maximum and average slightly decrease, 0.2% and 0.5% respectively. The slower maintenance personnel increase the lower the percent MC aircraft. Again, the minimum increases for excursions 1 and 2, but decreases for excursion 3.

Table 21. Scenario 1: Percent Mission-Capable Aircraft Normal

	Maximum Percent MC Aircraft	Average Percent MC Aircraft	Minimum Percent MC Aircraft
Baseline	99.4%	82.5%	50.2%
Excursion 1	99.3%	82.3%	50.9%
Excursion 2	99.2%	82.3%	51.5%
Excursion 3	99.2%	82.0%	49.6%

Table 22 depicts the percentage of sorties flown for scenario 1 using the Weibull distribution. In all cases, 100% of the scheduled sorties were able to be flown for the

maximum. The average shows a very small decrease in sorties flown the slower maintenance personnel increase, 0.07% from the baseline to excursion 3. The minimum shows a larger decrease, 3.25%, the slower maintenance personnel increases.

Table 22. Scenario 1: Percent Sorties Flown Weibull

	Maximum Percent Sorties Flown	Average Percent Sorties Flown	Minimum Percent Sorties Flown
Baseline	100.00%	99.98%	98.59%
Excursion 1	100.00%	99.96%	96.79%
Excursion 2	100.00%	99.94%	95.93%
Excursion 3	100.00%	99.91%	95.34%

Table 23 displays the percent of sorties flown for scenario 1 using the normal function. It shows very similar patterns to the Weibull function. All sorties are able to be flown for each excursion with a maximum of 100%. The average slightly decreases the slower maintenance personnel increases with the largest decrease being excursion 3 at 0.08%. The minimum decreases for each excursion but excursion 2 has a smaller decrease than excursions 1 and 3.

Table 23. Scenario 1: Percent Sorties Flown Normal

	Maximum Percent Sorties Flown	Average Percent Sorties Flown	Minimum Percent Sorties Flown
Baseline	100.00%	99.98%	97.86%
Excursion 1	100.00%	99.96%	96.66%
Excursion 2	100.00%	99.97%	97.79%
Excursion 3	100.00%	99.90%	95.59%

Figure 10 best displays the differences between MC aircraft for the baseline and excursions, using excursion 3 as an example. There is not a distinct difference between the maximums. However, there is a difference seen in the averages and minimums. The excursion average and excursion minimum clearly have fewer MC aircraft for the first 17 days. After these 17 days, the baseline and excursion 3 appear very similar. The reason there are fewer MC aircraft, is that maintenance personnel are slowly being increased over the first 20 days in this excursion. And not until the

maintenance personnel level reaches closer to the maximum level do the number of MC aircraft begin to match up between the baseline and excursion for both the average and minimum number of MC aircraft.

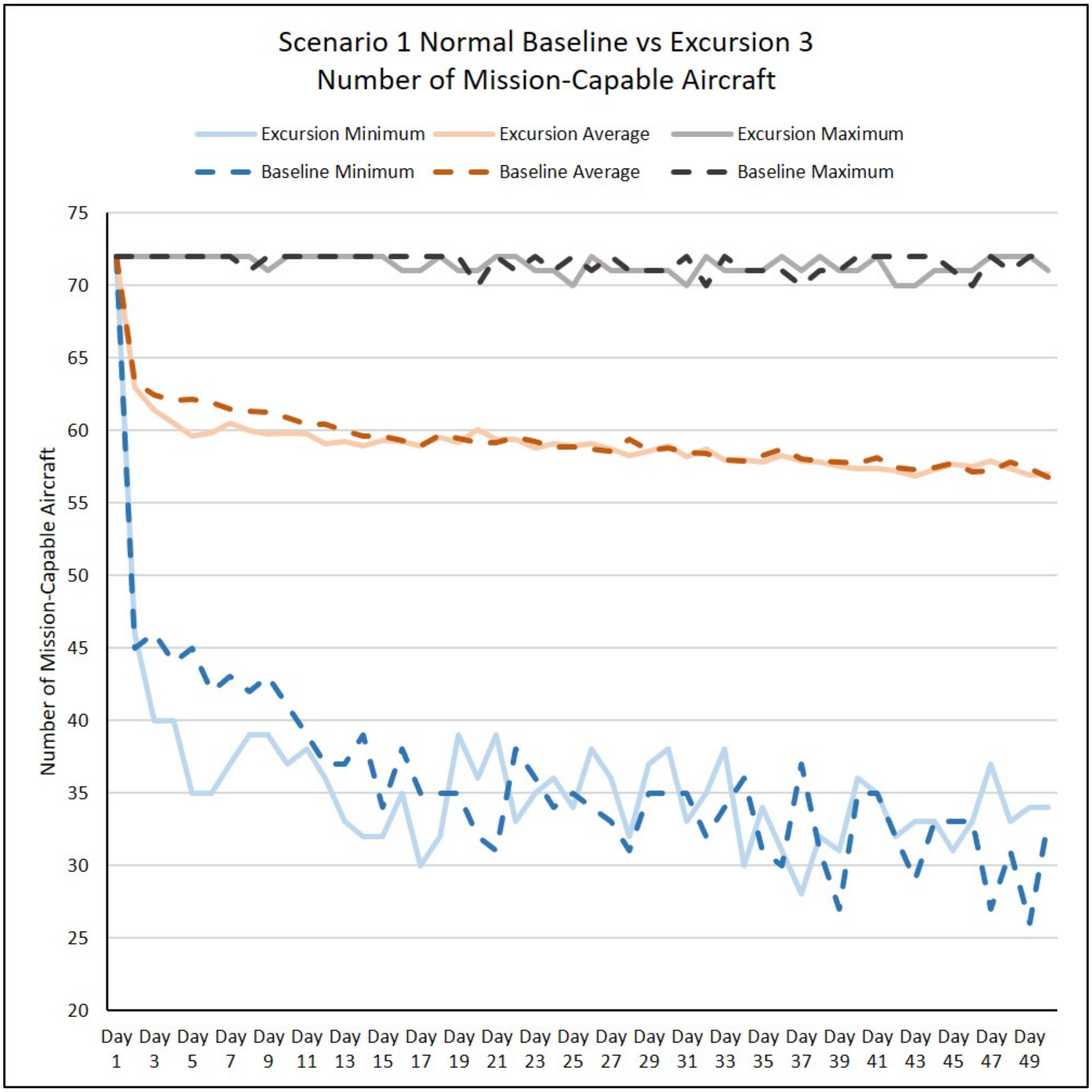


Figure 10. Scenario 1: Baseline versus Excursion 3 Number of MC Aircraft Normal

Figure 11 also shows the baseline versus excursion 3 but for number of sorties flown. The most obvious difference is the excursion minimum is much lower the first 14 days than the baseline. The excursion average also is below the baseline average from day 3 to day 15. Beyond day 15, the baseline and excursion are much more

similar. This plot also shows that slowly increasing maintenance personnel affects not only number of MC aircraft, but also number of sorties flown until a higher level of manning is attained.

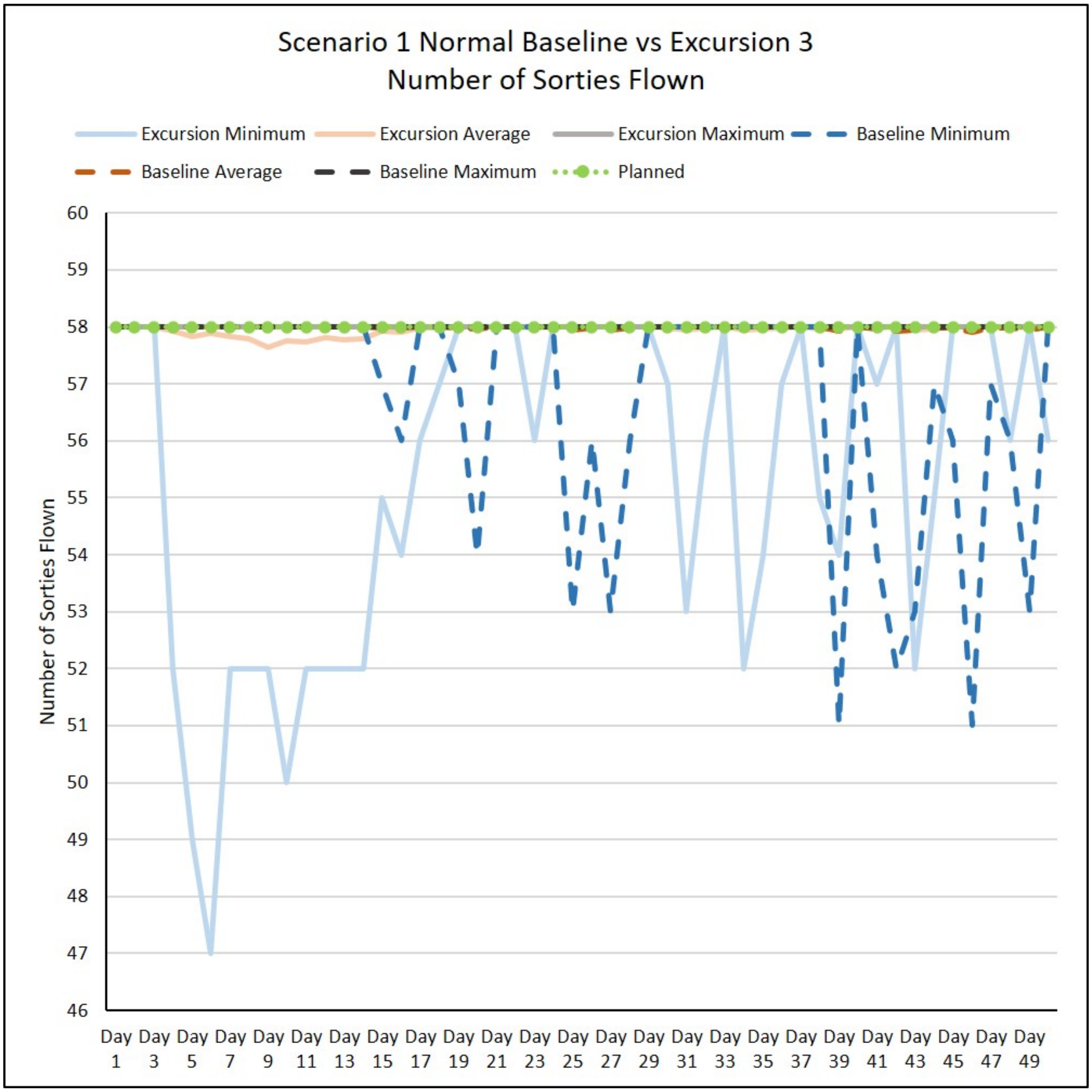


Figure 11. Scenario 1: Baseline versus Excursion 3 Number of Sorties Flown Normal

Scenario 1 baseline plots can be found in Figures 26 - 29 in Appendix D. Additional plots of the baseline versus other excursions can also be found in Appendix D in Figures 34 - 39.

4.1.3 Type of Aircraft

This section breaks out the percent of MC aircraft and percent of sorties flown by each airframe. Table 24 and Table 25 display the average percent of MC aircraft by type of aircraft for the Weibull and normal functions respectively. Generally, it is conjectured these percentages should decrease from the baseline to excursions as less maintenance personnel are available for longer periods of time. This is the case for the Weibull B-2, C-130, and KC-46, and the Normal C-130 and KC-46. The F-15 and F-16 have an increase in percentage in multiple excursions for the Weibull. For the normal, the B-2 and F-15 increase in percentage in excursion 3. The F-16 increases in excursion 2 for the normal function.

Table 24. Scenario 1: Average Percent MC Aircraft by Aircraft Weibull

Scenario 1	B-2	C-130	F-15	F-16	KC-46
Baseline	82.56%	83.30%	82.50%	81.81%	81.39%
Excursion 1	81.29%	82.51%	82.61%	82.51%	79.82%
Excursion 2	82.22%	82.05%	82.28%	82.38%	80.29%
Excursion 3	81.88%	82.89%	82.92%	82.29%	77.51%

Table 25. Scenario 1: Average Percent MC Aircraft by Aircraft Normal

Scenario 1	B-2	C-130	F-15	F-16	KC-46
Baseline	82.44%	83.92%	82.40%	82.68%	81.13%
Excursion 1	81.26%	83.85%	81.98%	83.16%	80.50%
Excursion 2	81.91%	82.41%	82.36%	82.78%	80.85%
Excursion 3	82.78%	83.46%	82.66%	82.03%	77.54%

Similarly, Table 26 and Table 27 show the average percent of sorties flown by aircraft for both functions. The F-15 and F-16 both flew 100% of sorties for both functions. The B-2 and KC-46 show decreasing sorties flown from the baseline which makes sense because the excursions have fewer personnel for a period of time. The C-130 shows increased sorties for excursion 3 when having fewer personnel in the Weibull. The normal C-130 shows the same percentage of sorties across the excursions

which is 0.04% less than the baseline. The B-2 normal shows increasing percentage of sorties in excursion 2.

Table 26. Scenario 1: Average Percent Sorties Flown by Aircraft Weibull

Scenario 1	B-2	C-130	F-15	F-16	KC-46
Baseline	99.99%	99.96%	100.00%	100.00%	99.90%
Excursion 1	99.94%	99.94%	100.00%	100.00%	99.73%
Excursion 2	99.95%	99.89%	100.00%	100.00%	99.56%
Excursion 3	99.90%	99.99%	100.00%	100.00%	99.28%

Table 27. Scenario 1: Average Percent Sorties Flown by Aircraft Normal

Scenario 1	B-2	C-130	F-15	F-16	KC-46
Baseline	99.95%	99.99%	100.00%	100.00%	99.85%
Excursion 1	99.94%	99.95%	100.00%	100.00%	99.71%
Excursion 2	99.98%	99.95%	100.00%	100.00%	99.80%
Excursion 3	99.89%	99.95%	100.00%	100.00%	99.21%

The slow increase of maintenance personnel does cause a reduction in MC aircraft and sorties flown at the beginning of each excursion. However, the non-MC aircraft and missed sorties are so slight, they do not affect the 50 day totals. This is seen by the similar percentages of MC aircraft and sorties flown throughout scenario 1.

Plots of average number of MC aircraft and average number of sorties flown broken out by type of aircraft are in Appendix D, Figures 69, 73, 77, 81, and 85 for the B-2, C-130, F-15, F-16, and KC-46 respectively.

4.1.4 Scenario 1 Insights

Scenario 1 does not stress the limits of MTBF and MTTR as shown by Table 20 and Table 21 the maximum percent of MC aircraft is over 99%. Table 22 and Table 23 also proves this with 100% of sorties flown for the maximum and 99.9% or greater of sorties flown for the average. Figure 10 and Figure 11 display a large variation in the minimum number of MC aircraft and number of sorties flown.

However, scenario 1 does show there is a significant difference between functions for the average number of MC aircraft.The minimum and maximum number of MC aircraft do not show a statistical significant difference, nor does there appear to be a significant difference in sorties flown.

Also from scenario 1, it appears that slowly increasing personnel has a slight effect on the number of MC aircraft and number of sorties flown. The slower personnel increases, fewer MC aircraft and sorties flown can be expected. The number of MC aircraft and number of sorties flown are slightly reduced until a larger personnel presence exists.

4.2 Scenario 2 Results, Analysis, and Insights

4.2.1 Normal versus Weibull

Comparing the normal and Weibull number of mission-capable aircraft and number of sorties flown for scenario 2, there is no significant difference between the models for either output. Table 28 displays the P values for number of MC aircraft and all are above the α value of 0.05. Similarly, Table 29 shows the P values for number of sorties flown with no resulting P values below 0.05. The maximum number of sorties flown could not be compared since all sorties were flown across the baseline and excursions.

Table 28. Scenario 2: Paired T-test *P* Values for Number of MC Aircraft

	Maximum *P* Value	**Average *P* Value**	**Minimum *P* Value**
Baseline	0.103	0.204	0.486
Excursion 1	0.290	0.170	0.163
Excursion 2	0.605	0.839	0.320

Scenario 2, excursion 2, in Figure 12, best displays how dissimilar the normal and Weibull functions are for this scenario in number of MC aircraft. There is no distinct

Table 29. Scenario 2: Paired T-test P Values for Number of Sorties Flown

	Maximum P Value	Average P Value	Minimum P Value
Baseline	NA	0.202	0.072
Excursion 1	NA	0.082	0.870
Excursion 2	NA	0.175	0.369

difference in the maximums, averages, or minimums, and in fact the averages appear nearly identical.

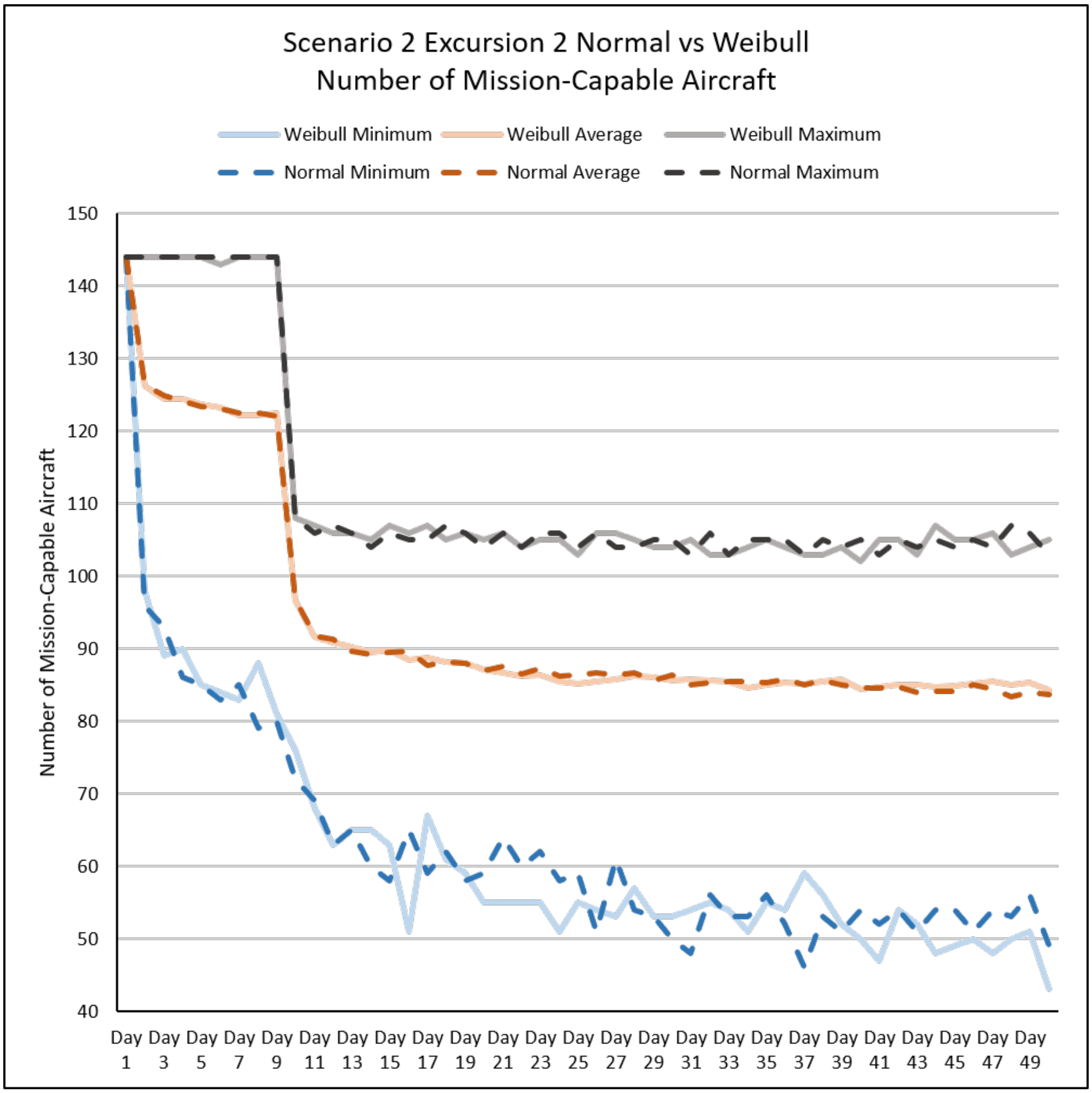


Figure 12. Scenario 2: Excursion 2 Normal versus Weibull Number of MC Aircraft

Figure 13 shows a similar trend as Figure 12 but in number of sorties flown. Day 10 does show the normal minimum much lower than the Weibull, but the Weibull is much lower than the normal on day 18. Other than these distinct differences, the number of sorties flown is extremely similar between the two functions. Both figures display variability in the minimum values.

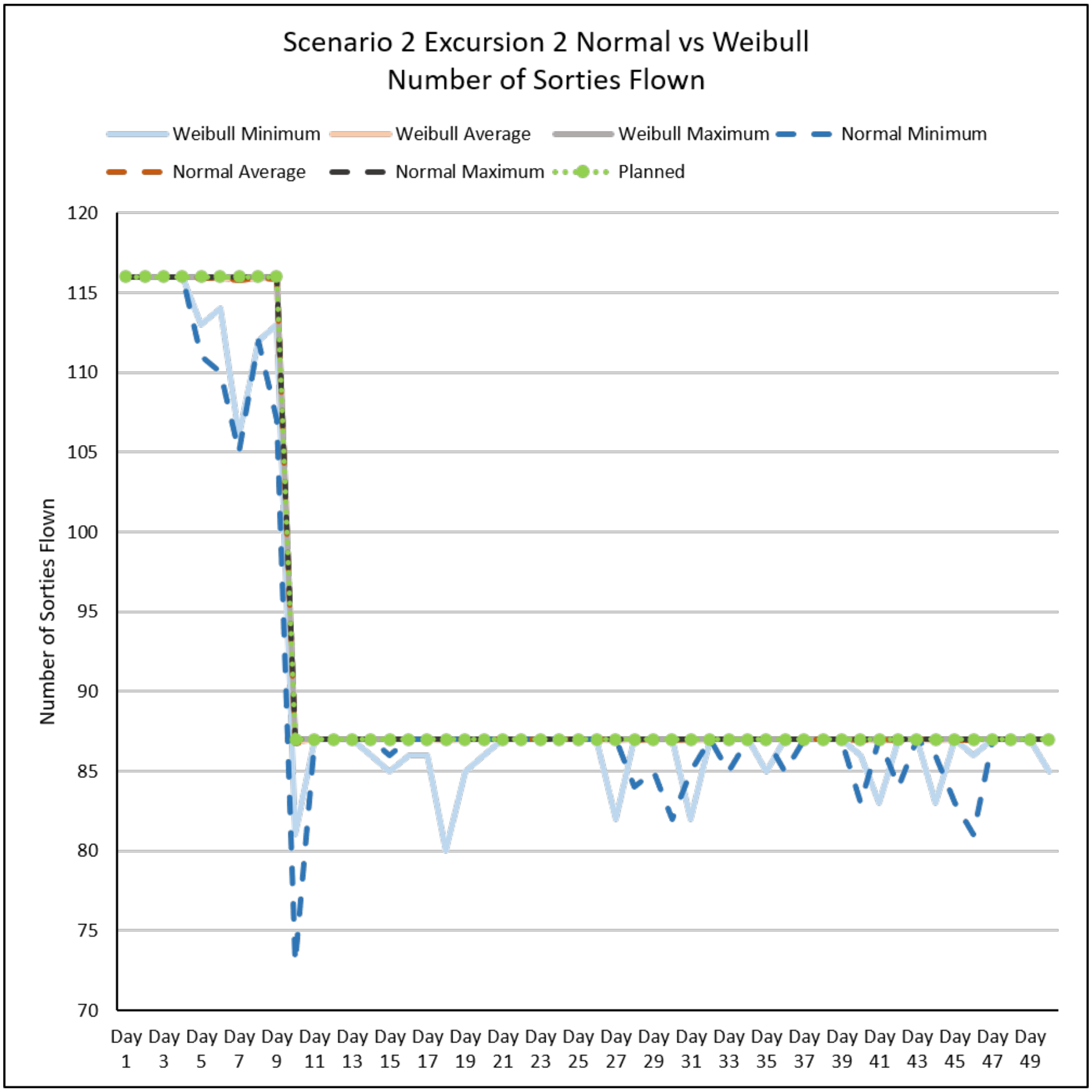


Figure 13. Scenario 2: Excursion 2 Normal versus Weibull Number of Sorties Flown

Figures 40 - 42 in Appendix D display the normal versus Weibull plots for all excursions for this scenario.

4.2.2 Baseline versus Excursions

Moving on to the scenario 2 baseline and excursions, Table 30 shows the percent of MC aircraft for scenario 2 using the Weibull function. The baseline models 2 bases operating at median capacity, and the maximum, average, and minimum MC rates are 99.4%, 81.4% and 48.1% respectively. Excursion 1 reduces base 1's operating capacity from median to the 25th percentile while base 2 remains unchanged. The maximum remains the same, the average increases by 1% and the minimum decreases by 0.7%. Excursion 2 models one base operating at the 75th percentile. Comparing this excursion to the other two, the maximum decreased to 97.7%, the average is in between the others at 81.8% and the minimum saw the largest change, increasing to 54.3%.

Table 30. Scenario 2: Percent MC Aircraft Weibull

	Maximum Percent MC Aircraft	**Average Percent MC Aircraft**	**Minimum Percent MC Aircraft**
Baseline	99.4%	81.4%	48.1%
Excursion 1	99.4%	82.4%	47.4%
Excursion 2	97.7%	81.8%	54.3%

Table 31 shows the percent of MC aircraft for scenario 2 using the normal function. These results are very similar to the Weibull results. The baseline's maximum percent of MC aircraft is 99.1%, the average is 81.5% and the minimum is 48.5%. Excursion 1 percentages increase again when personnel are decreased; the maximum and average increase by 0.4% and 0.7% respectively but the minimum decreases by 0.8%. Excursion 2 shows a larger decrease in the maximum, an average in between the previous 2 excursions at 81.8% and a significantly larger increase in the minimum, up to 54.9%..

The percent of sorties flown using the Weibull function are shown in Table 32. The maximum across all excursions is 100%. The average baseline flew 99.76% of sorties with the average of excursion 1 slightly decreasing and the average of excursion

Table 31. Scenario 2: Percent MC Aircraft Normal

	Maximum Percent MC Aircraft	Average Percent MC Aircraft	Minimum Percent MC Aircraft
Baseline	99.1%	81.5%	48.5%
Excursion 1	99.5%	82.2%	46.7%
Excursion 2	97.8%	81.8%	54.9%

2 slightly increasing. The minimum in the baseline is 91.17% with excursion 1's minimum at 89.24% and excursion 2's minimum largely increasing to 98.55%.

Table 32. Scenario 2: Percent Sorties Flown Weibull

	Maximum Percent Sorties Flown	Average Percent Sorties Flown	Minimum Percent Sorties Flown
Baseline	100.00%	99.76%	91.17%
Excursion 1	100.00%	99.70%	89.24%
Excursion 2	100.00%	99.98%	98.55%

Again the normal function results are very similar to the Weibull and can be seen in Table 33. The maximum for all excursions is 100%. Similar changes in the percentages across scenarios are present here as well. The baseline average is 99.79% and very slightly decreases for excursion 1 and increases for excursion 2. There is a 2.88% percent decrease in the minimum between the baseline and excursion 1 while there is a 5.97% increase between the baseline and excursion 2.

Table 33. Scenario 2: Percent Sorties Flown Normal

	Maximum Percent Sorties Flown	Average Percent Sorties Flown	Minimum Percent Sorties Flown
Baseline	100.00%	99.79%	92.21%
Excursion 1	100.00%	99.74%	89.33%
Excursion 2	100.00%	99.97%	98.18%

Figure 14 compares the number of MC aircraft from excursion 1 to excursion 2 when using the Weibull function. Excursion 1 has more maximum MC aircraft, and more average MC aircraft for the majority of the last half of the simulation. The minimum number of MC aircraft for excursion 1 is much lower than excursion 2's minimum.

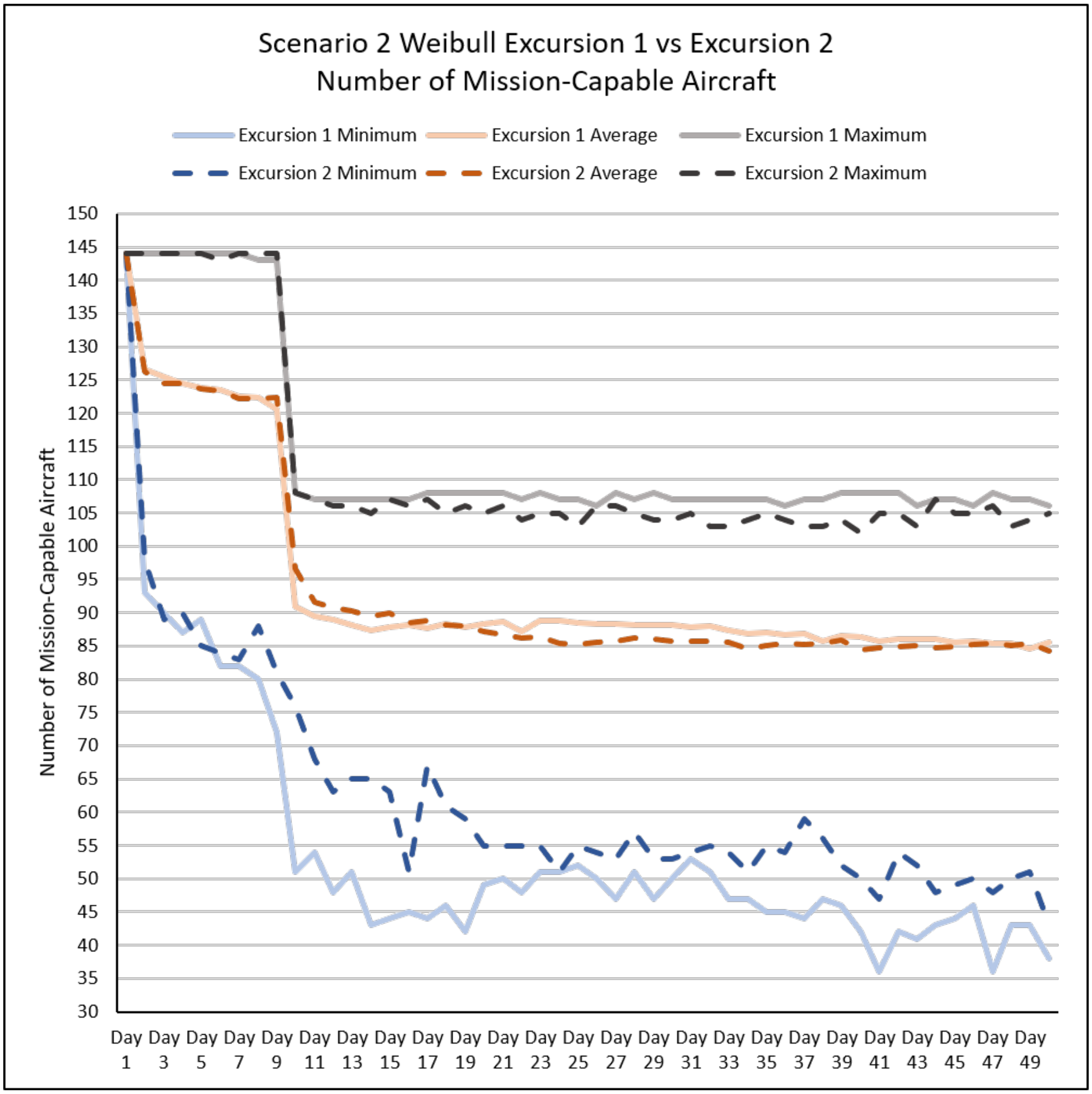


Figure 14. Scenario 2: Excursion 1 versus Excursion 2 Number of MC Aircraft Weibull

Figure 15 shows the number of sorties flown for excursions 1 and 2 for scenario 2. Excursion 1 has a much lower minimum, and a slightly lower average than excursion 2, with the maximums being the same. Operating at a single base results in less MC aircraft but more sorties flown.

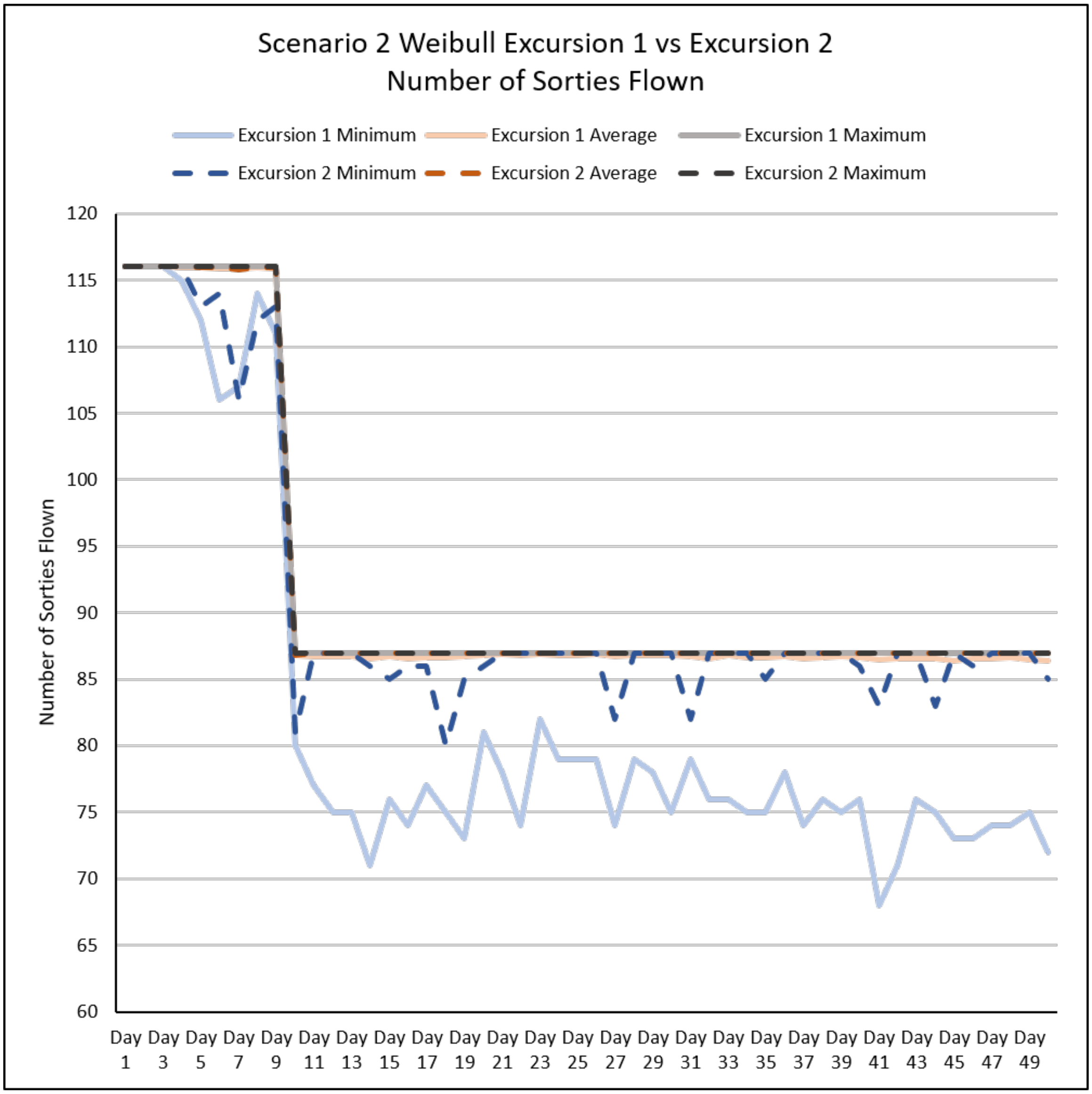


Figure 15. Scenario 2: Excursion 1 versus Excursion 2 Number of Sorties Flown Weibull

The baseline plots for this scenario can be found in Appendix D in Figures 26-29. Figures 43 through 48 are plots of comparisons of the baseline and excursions, also in Appendix D.

4.2.3 Type of Aircraft

When breaking out the results by type of aircraft, Table 34 and Table 35 show the average percent of MC aircraft for both the Weibull and normal functions, respectively. The baseline for the Weibull has the highest percentage of MC aircraft for the B-2 and C-130, but the lowest percentage for the KC-46. The baseline percent of MC aircraft for the fighters falls in between the two excursions. The normal baseline percentages show no trends. Excursion 1 shows the highest percentage for fighters but the lowest percentage for the C-130. The KC-46 is the only airframe that shows major differences between excursions with nearly a 7% difference between the baseline and excursion 2.

Table 34. Scenario 2: Average Percent MC Aircraft by Aircraft Weibull

Scenario 2	B-2	C-130	F-15	F-16	KC-46
Baseline	84.21%	84.21%	82.14%	82.41%	71.73%
Excursion 1	83.03%	83.03%	83.43%	83.14%	74.22%
Excursion 2	83.36%	83.36%	81.68%	81.61%	78.68%

Table 35. Scenario 2: Average Percent MC Aircraft by Aircraft Normal

Scenario 2	B-2	C-130	F-15	F-16	KC-46
Baseline	83.52%	83.60%	82.41%	82.30%	72.35%
Excursion 1	83.52%	84.17%	82.85%	83.30%	73.91%
Excursion 2	83.56%	84.27%	81.39%	81.70%	79.12%

Table 36 and Table 37 show the average percent of sorties flown by aircraft for both functions. Perhaps most noticeable is the F-15 and F-16 flew all sorties across all excursions and functions. Excursion 1 flew the least sorties for the non-fighter aircraft, followed by the baseline, and excursion 2 flying the most sorties. The values between functions are also very similar.

Individual plots of each aircraft can be found in Appendix D in Figures 70, 74, 78, 82, and 86.

Table 36. Scenario 2: Average Percent of Sorties Flown by Aircraft Weibull

Scenario 2	B-2	C-130	F-15	F-16	KC-46
Baseline	99.95%	99.94%	100.00%	100.00%	97.83%
Excursion 1	99.71%	99.80%	100.00%	100.00%	97.64%
Excursion 2	99.99%	100.00%	100.00%	100.00%	99.81%

Table 37. Scenario 2: Average Percent Sorties Flown by Aircraft Normal

Scenario 2	B-2	C-130	F-15	F-16	KC-46
Baseline	99.96%	99.97%	100.00%	100.00%	98.04%
Excursion 1	99.72%	99.83%	100.00%	100.00%	97.95%
Excursion 2	99.99%	100.00%	100.00%	100.00%	99.74%

4.2.4 Scenario 2 Insights

Scenario 2 also does not stress the maintenance personnel limits due to the nearly 99% MC rates in Table 30 and Table 31 and the 100% sorties flown in Table 32 and Table 33. Figure 14 and Figure 15 continue to show large variability in the minimum number of MC aircraft and sorties flown.

Scenario 2 shows no significant difference between the Weibull and Normal functions. Comparing the percentages shows that the values are indeed very similar. There are no trends between baseline and excursions concerning MC aircraft. When it comes to base consolidation, combining personnel and aircraft at a single base may be the best option. While there is a decrease in maximum and average number of MC aircraft, the large increase in minimum number of MC aircraft may outweigh these. The number of sorties flown also increases when consolidating to a single base, with the minimum number of sorties flown greatly outperforming the other excursions.

4.3 Scenario 3 Results, Analysis, and Insights

4.3.1 Normal versus Weibull

Comparing the normal and Weibull results in Table 38 for MC aircraft, there is a statistical significant difference between the functions. The maximum number of MC aircraft is significantly different for the baseline and excursion 3 only. However, the average number of MC aircraft is significantly different across all excursions including the baseline. The minimum is only different for excursion 1.

Table 38. Scenario 3: Paired T-test *P* Values for Number of MC Aircraft

	Maximum *P* Value	Average *P* Value	Minimum *P* Value
Baseline	0.007	0.000	0.898
Excursion 1	1.000	0.040	0.003
Excursion 2	0.890	0.000	0.118
Excursion 3	0.002	0.000	0.946

Table 39 shows the significant difference between the normal and Weibull functions for sorties flown. Again the maximums could not be compared since all sorties were flown for the maximum across all excursions and the baseline. The average number of sorties flown is significantly different for the baseline and excursions since the P value is less than the α value of 0.05. The minimum sorties flown is only different for excursions 1 and 2.

Table 39. Scenario 3: Paired T-test *P* Values for Number Sorties Flown

	Maximum *P* Value	Average *P* Value	Minimum *P* Value
Baseline	NA	0.001	0.508
Excursion 1	NA	0.000	0.044
Excursion 2	NA	0.039	0.000
Excursion 3	NA	0.001	0.243

Figure 16 compares the normal and Weibull function MC aircraft results for scenario 3, excursion 2. Despite appearing very similar, the average and minimum

number of MC aircraft are statistically different.

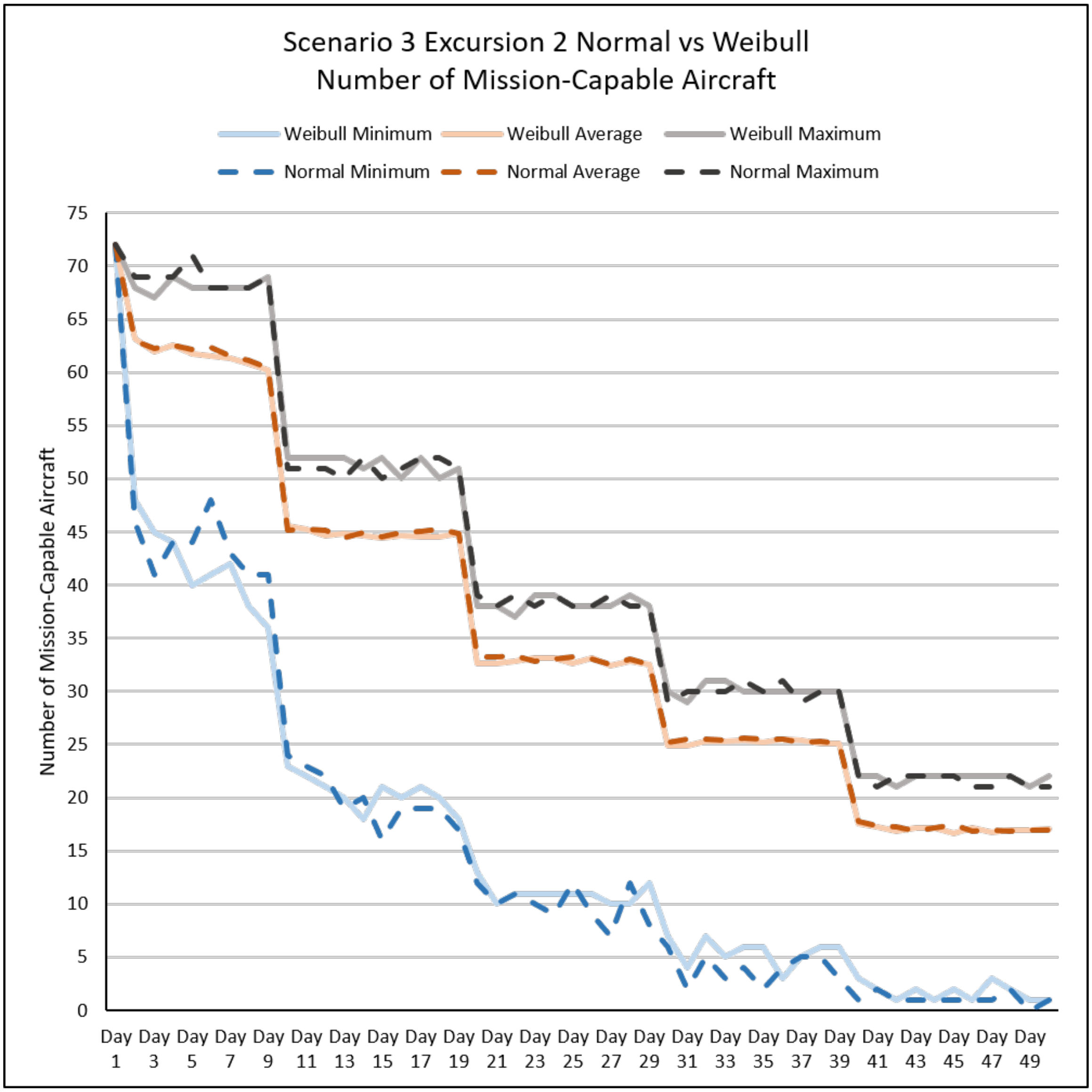


Figure 16. Scenario 3: Excursion 2 Normal versus Weibull Number of MC Aircraft

The average and minimums for number of sorties flown are also significantly different and are shown in Figure 17.

Plots of the normal and Weibull comparison for the remaining excursions are in Appendix D, Figures 49 to 52.

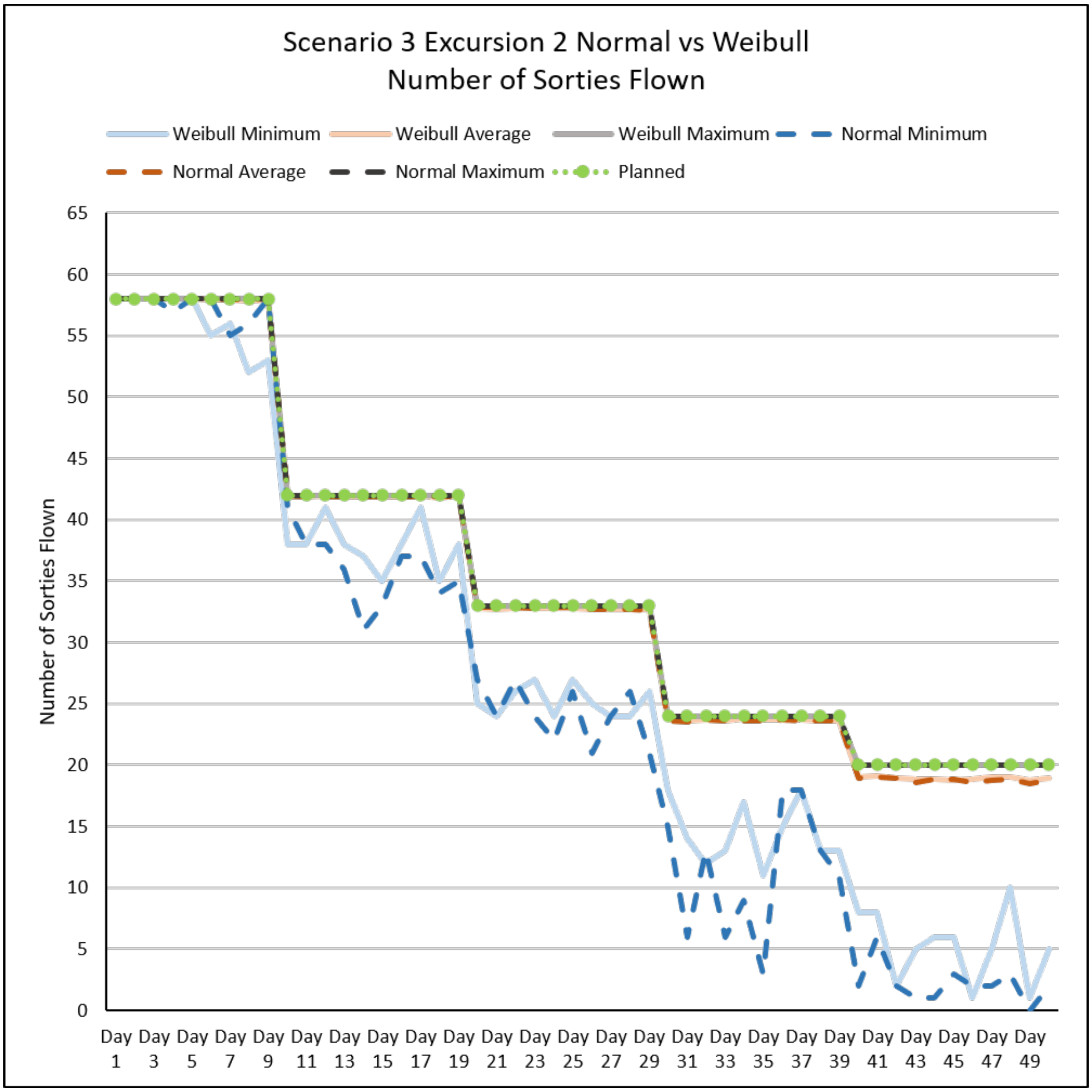


Figure 17. Scenario 3: Excursion 2 Normal versus Weibull Number of Sorties Flown

4.3.2 Baseline versus Excursions

The baseline maximum percent MC aircraft for the Weibull function is 95.4% in Table 40. All excursions show a slight increase between 0.6% and 0.9%. The average percent of MC aircraft increases in excursion 1 and decreases in excursions 2 and 3. All excursions remain within plus or minus 0.4% of the baseline. The minimum shows the most change in percent MC aircraft with excursion 1 increasing by 2.9% to 39.1%, excursion 2 increasing by 0.9% to 37.1% and excursion 3 decreasing by 0.1% to 36.1%.

Table 40. Scenario 3: Percent MC Aircraft Weibull

	Maximum Percent MC Aircraft	**Average Percent MC Aircraft**	**Minimum Percent MC Aircraft**
Baseline	95.4%	83.5%	36.2%
Excursion 1	96.3%	83.9%	39.1%
Excursion 2	96.0%	83.2%	37.1%
Excursion 3	96.2%	83.3%	36.1%

The baseline maximum percent MC aircraft for the normal function is 96.2% in Table 41. Excursions 1 and 2 remain relatively unchanged with percentages of 96.3 and 96.0 respectively. Excursion 3 decreases by 1%. The average for the baseline is 84.3%. Excursion 1 is very similar at 84.1% but excursions 2 and 3 decrease slightly more at 83.6% and 82.8% respectively. The minimum for the baseline is 36.1%. Excursion 1 increases to 37.4% while excursion 2 decreases to 35.9%. Excursion 3 remains close to the baseline at 36.0%.

Table 41. Scenario 3: Percent MC Aircraft Normal

	Maximum Percent MC Aircraft	**Average Percent MC Aircraft**	**Minimum Percent MC Aircraft**
Baseline	96.2%	84.3%	36.1%
Excursion 1	96.3%	84.1%	37.4%
Excursion 2	96.0%	83.6%	35.9%
Excursion 3	95.2%	82.8%	36.0%

The percent sorties flown for the Weibull function maximum is 100% for all excur-

sions as seen in Table 42. The averages are all close with the baseline flying 98.88% of sorties with only excursion 2 flying more at 98.91%. Excursions 1 and 3 fly less with 98.80% and 98.60% respectively. The minimum for the baseline and excursion 2 are similar at 77.60% and 77.25% respectively. Excursion 2's minimum increases to 80.83% while excursion 3's minimum decreases to 72.11% from the baseline.

Table 42. Scenario 3: Percent Sorties Flown Weibull

	Maximum Percent Sorties Flown	Average Percent Sorties Flown	Minimum Percent Sorties Flown
Baseline	100.00%	98.88%	77.60%
Excursion 1	100.00%	98.80%	80.83%
Excursion 2	100.00%	98.91%	77.25%
Excursion 3	100.00%	98.60%	72.11%

Table 43 shows the percent of sorties flown for each excursion using the normal function. The maximums remain at 100%. The baseline average is 99.05% and slightly decreases between each excursion. The minimums do not always decrease, as excursion 1 increases from 76.56% in the baseline to 81.76%. Excursions 2 and 3 decrease from the baseline to 72.40% and 74.02% respectively.

Table 43. Scenario 3: Percent Sorties Flown Normal

	Maximum Percent Sorties Flown	Average Percent Sorties Flown	Minimum Percent Sorties Flown
Baseline	100.00%	99.05%	76.56%
Excursion 1	100.00%	98.89%	81.76%
Excursion 2	100.00%	98.82%	72.40%
Excursion 3	100.00%	98.77%	74.02%

Figure 18 compares the baseline to excursion 3 using the normal function for MC aircraft. The maximum and average are slightly lower than the baseline, with the minimum being very identical.

Figure 19 shows the difference in sorties flown between the baseline and excursion 3. Here, the average and minimums are lower for the excursion with the maximum's being the same.

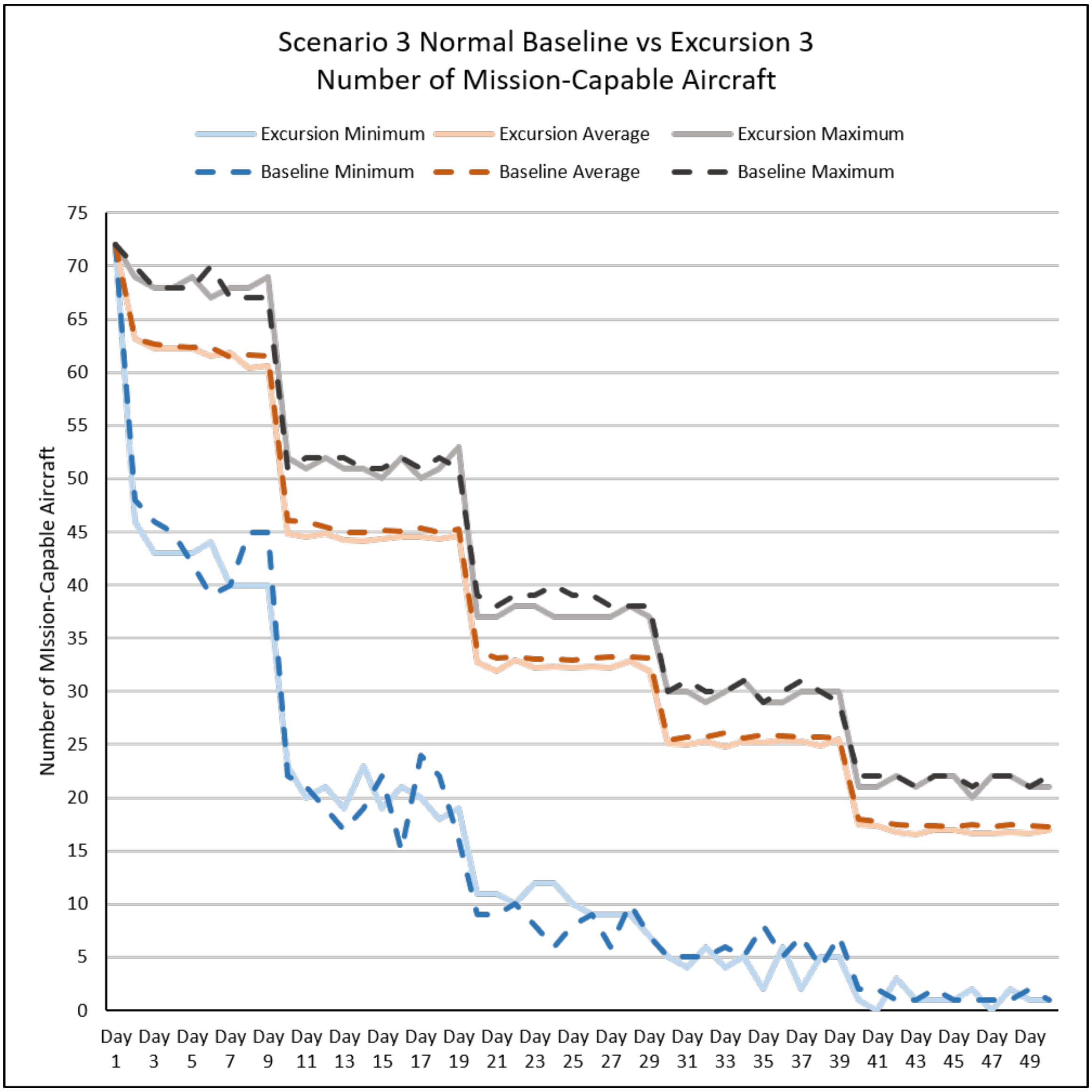


Figure 18. Scenario 3: Baseline versus Excursion 3 Number of MC Aircraft Normal

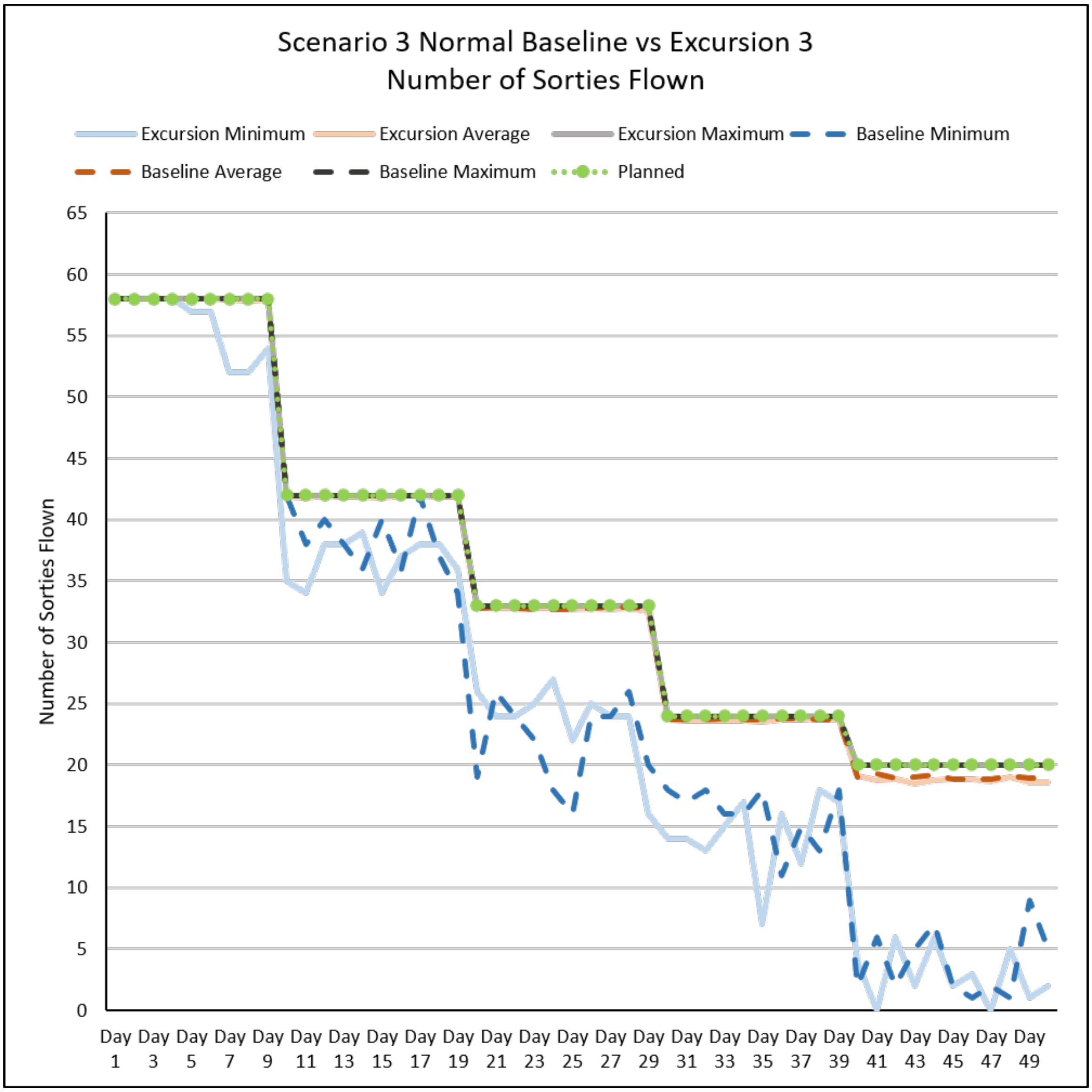


Figure 19. Scenario 3: Baseline versus Excursion 3 Number of Sorties Flown Normal

The baseline plots for this scenario can be found in Appendix D, Figures 26 to 29. Plots of all baseline and excursion comparisons for this scenario are in Figures 53 - 58 in Appendix D.

4.3.3 Type of Aircraft

Since aircraft were randomly destroyed for this scenario, it cannot be determined how many of each aircraft were present throughout the simulation. This means the percentage of MC aircraft broken down by airframe cannot be calculated. Since the number of sorties flown and scheduled is known, only these will be compared.

Table 44 and Table 45 display the percent of sorties flown by aircraft for both functions. There are a similar percentage of sorties flown across the excursions and functions. There are no discernible patterns in either of these tables.

Table 44. Scenario 3: Average Percent Sorties Flown by Aircraft Weibull

Scenario 3	B-2	C-130	F-15	F-16	KC-46
Baseline	96.57%	97.18%	99.76%	99.70%	96.61%
Excursion 1	96.19%	96.43%	99.87%	99.83%	95.99%
Excursion 2	97.78%	96.58%	99.81%	99.77%	95.78%
Excursion 3	95.89%	95.99%	99.80%	99.58%	95.81%

Table 45. Scenario 3: Average Percent Sorties Flown by Aircraft Normal

Scenario 3	B-2	C-130	F-15	F-16	KC-46
Baseline	97.13%	97.42%	99.86%	99.65%	97.42%
Excursion 1	97.06%	96.43%	99.87%	99.83%	95.99%
Excursion 2	97.39%	97.58%	99.62%	99.67%	95.33%
Excursion 3	96.46%	97.70%	99.49%	99.75%	95.84%

Figures 71, 75, 79, 83, and 87 plot the average number of MC aircraft and sorties flown by type of aircraft and can be found in Appendix D.

4.3.4 Scenario 3 Insights

Scenario 3 did not strain the MTTR models. This is evidenced by the 100% of maximum sorties flown and 99% of average sorties flown in Table 42 and Table 43. The minimum number of MC aircraft and minimum number of sorties flown again shows large variability in Figure 18 and Figure 19.

Scenario 3 showed a significant difference in the average number of MC aircraft and average number of sorties flown. The maximums and minimums for these generally did not show a significant difference. The percent of MC aircraft and sorties flown showed no major changes between the baseline and excursions. This makes sense because both aircraft and personnel are being attrited at similar rates, thus keeping the personnel to aircraft ratio similar which should not result in a significant change. There is more variation in the minimum percent of MC aircraft and minimum percent sorties flown.

4.4 Scenario 4 Results, Analysis, and Insights

4.4.1 Normal versus Weibull

Table 46 and Table 47 show the statistical comparison between the normal and Weibull functions for number of MC aircraft and number of sorties flown for scenario 4. Table 46 shows the statistical significant difference for number of MC aircraft. There is no difference in the maximum and minimum number of MC aircraft for the two functions. However, there is a significant difference in the average number of MC aircraft for the baseline and both excursions.

Table 47 shows the statistical difference in number of sorties flown. The only significant difference is the average number of sorties flown for excursion 1. Otherwise, there is no difference or no comparison could be made.

Table 46. Scenario 4: Paired T-test *P* Values for Number of MC Aircraft

	Maximum *P* Value	Average *P* Value	Minimum *P* Value
Baseline	1.000	0.000	0.444
Excursion 1	0.192	0.000	0.198
Excursion 2	0.375	0.000	0.414

Table 47. Scenario 4: Paired T-test *P* Values for Number of Sorties Flown

	Maximum *P* Value	Average *P* Value	Minimum *P* Value
Baseline	NA	0.241	0.215
Excursion 1	NA	0.000	0.611
Excursion 2	NA	0.653	0.913

Figure 20 compares the normal and Weibull functions' results for excursion 1, number of MC aircraft. There is a statistical difference for the average number of MC aircraft which is clearly seen by the normal average above the Weibull average. The maximum and minimum appear very similar and are not statistically different.

Figure 21 compares the normal and Weibull functions' results for number of sorties flown. Again, only the average number of sorties flown are statistically different. The normal average has more sorties flown than the Weibull average. The maximum sorties flown are the same and minimums are similar but not significantly different.

Additional normal versus Weibull plots for this scenario can be found in Appendix D in Figures 59 to 62.

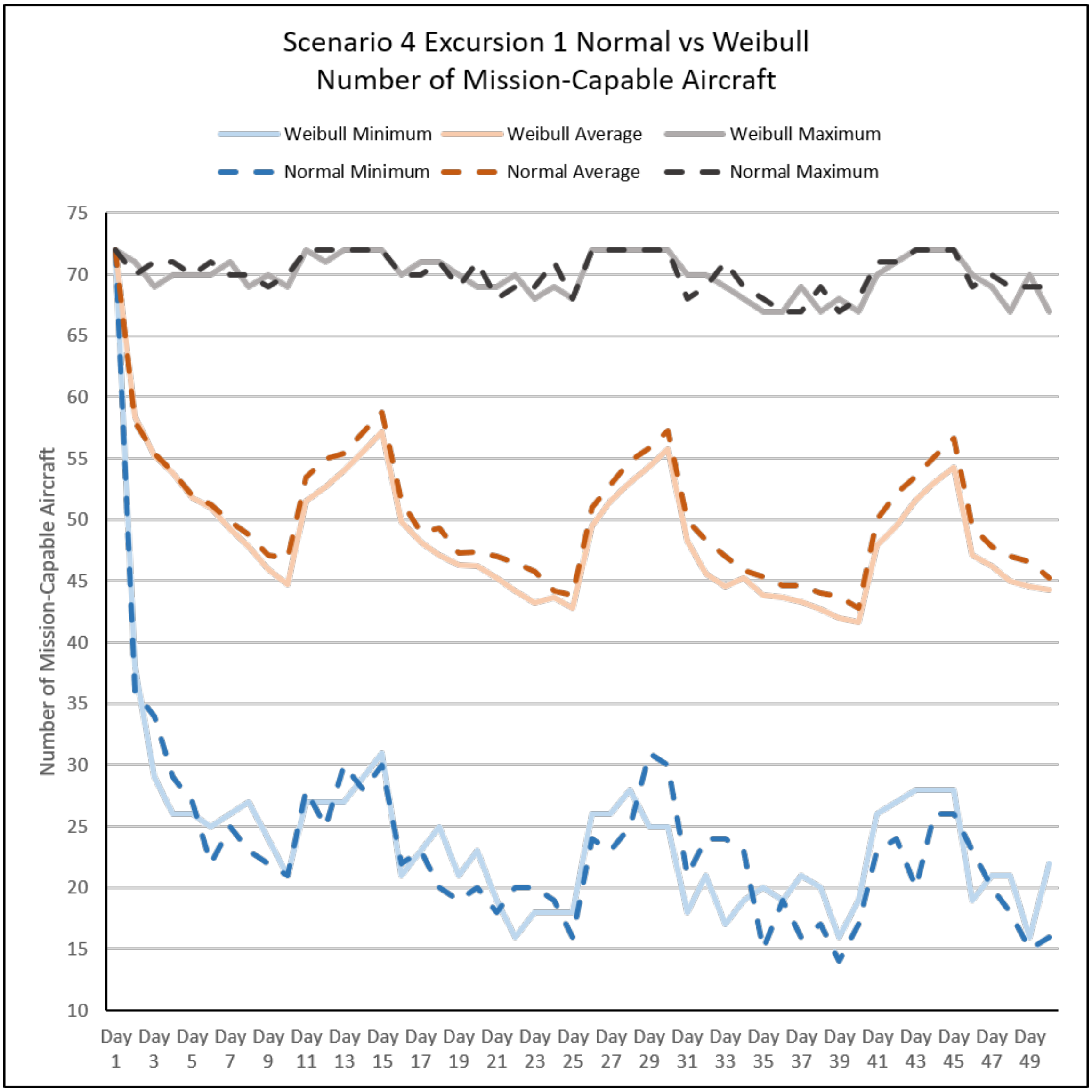


Figure 20. Scenario 4: Excursion 1 Normal versus Weibull Number of MC Aircraft

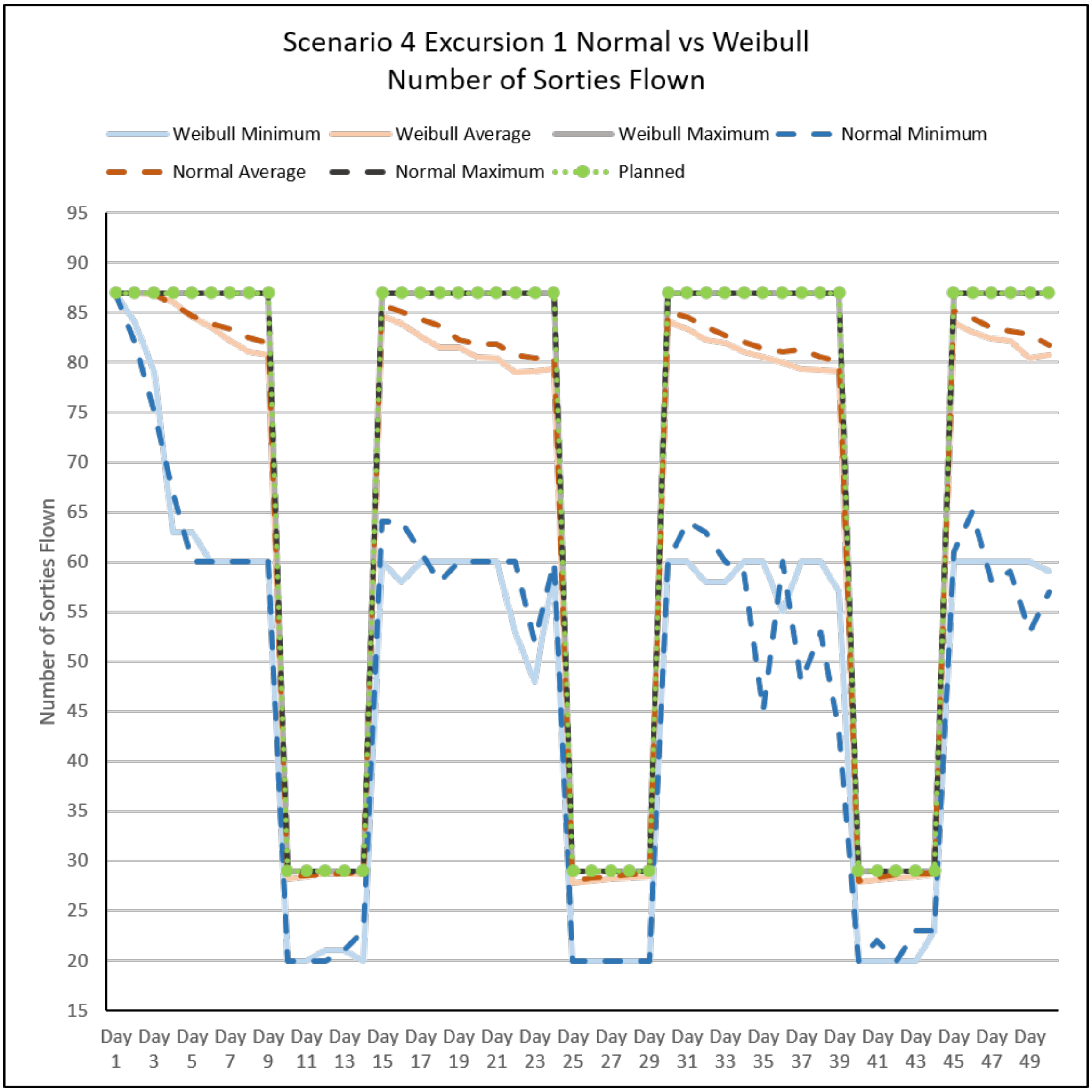


Figure 21. Scenario 4: Excursion 1 Normal versus Weibull Number of Sorties Flown

4.4.2 Baseline versus Excursions

The percent of MC aircraft for the Weibull function is shown in Table 48. The percent of MC aircraft is 98.1% for the baseline maximum which is median personnel and it is also 98.1% for excursion 2 which is maximum personnel. Excursion 1 which is minimum personnel is 97.1%. For the average, the baseline is 76.5% and decreases to 67.9% for excursion 1 and increases to 78.0% for excursion 2. The minimum shows a similar pattern and decreases from 41.3% in the baseline to 33.7% in excursion 1. Excursion 2 increases to 43.7%.

Table 48. Scenario 4: Percent MC Aircraft Weibull

	Maximum Percent MC Aircraft	Average Percent MC Aircraft	Minimum Percent MC Aircraft
Baseline	98.1%	76.5%	41.3%
Excursion 1	97.1%	67.9%	33.7%
Excursion 2	98.1%	78.0%	43.7%

The normal function results for MC aircraft in Table 49 are quite similar. The baseline maximum of 98.1% is decreased in excursion 1 to 97.4% and increased in excursion 2 to 98.3%. There is also a 7.3% decrease in excursion 1 from the baseline average of 77.3%. Excursion 3 offers a 1.3% increases from the baseline. The baseline minimum is 41.8% with excursion 1 decreasing to 32.9% and excursion 2 increasing to 43.1%.

Table 49. Scenario 4: Percent MC Aircraft Normal

	Maximum Percent MC Aircraft	Average Percent MC Aircraft	Minimum Percent MC Aircraft
Baseline	98.1%	77.3%	41.8%
Excursion 1	97.4%	70.0%	32.9%
Excursion 2	98.3%	78.6%	43.1%

The maximum percent of sorties flown is 100% for all excursions using the Weibull function. This can be seen in Table 50. The average sorties flown for the baseline is 99.16% and decreases in excursion 1 to 94.83% while increasing in excursion 2 to

99.75%. Similarly, the minimum percent of sorties flown is 84.43% in the baseline, 70.29% in excursion 1 and 88.56% in excursion 2.

Table 50. Scenario 4: Percent Sorties Flown Weibull

	Maximum Percent Sorties Flown	Average Percent Sorties Flown	Minimum Percent Sorties Flown
Baseline	100.00%	99.16%	84.43%
Excursion 1	100.00%	94.83%	70.29%
Excursion 2	100.00%	99.75%	88.56%

Again the maximum number of sorties flown for the normal in all excursions is 100% in Table 51. There is a decrease in sorties flown between the baseline and excursion 1 from 99.10% to 95.99%. Excursion 2 increases from the baseline to 99.76%. The minimum baseline and excursion 3 are closer in relation with 85.72% and 88.68% of sorties flown respectively. Excursion 1 shows a large drop off in the minimum percent of sorties flown with 69.83%.

Table 51. Scenario 4: Percent Sorties Flown Normal

	Maximum Percent Sorties Flown	Average Percent Sorties Flown	Minimum Percent Sorties Flown
Baseline	100.00%	99.10%	85.72%
Excursion 1	100.00%	95.99%	69.83%
Excursion 2	100.00%	99.76%	88.68%

Comparing the baseline to excursion 1 in Figure 22, there is a clear difference in average number of MC aircraft and minimum number of MC aircraft. The baseline, with median personnel, clearly out performs excursion 1 with minimum personnel.

Similarly, number of sorties flown between the baseline and excursion 1 can be found in Figure 23. The baseline distinctly flies more average and minimum sorties than excursion 1, indicating median personnel also guarantees more sorties than minimum personnel.

The baseline plots for this scenario are in Figures 26-29 in Appendix D. The baseline versus excursion plots are in Figures 63 to 68 in Appendix D.

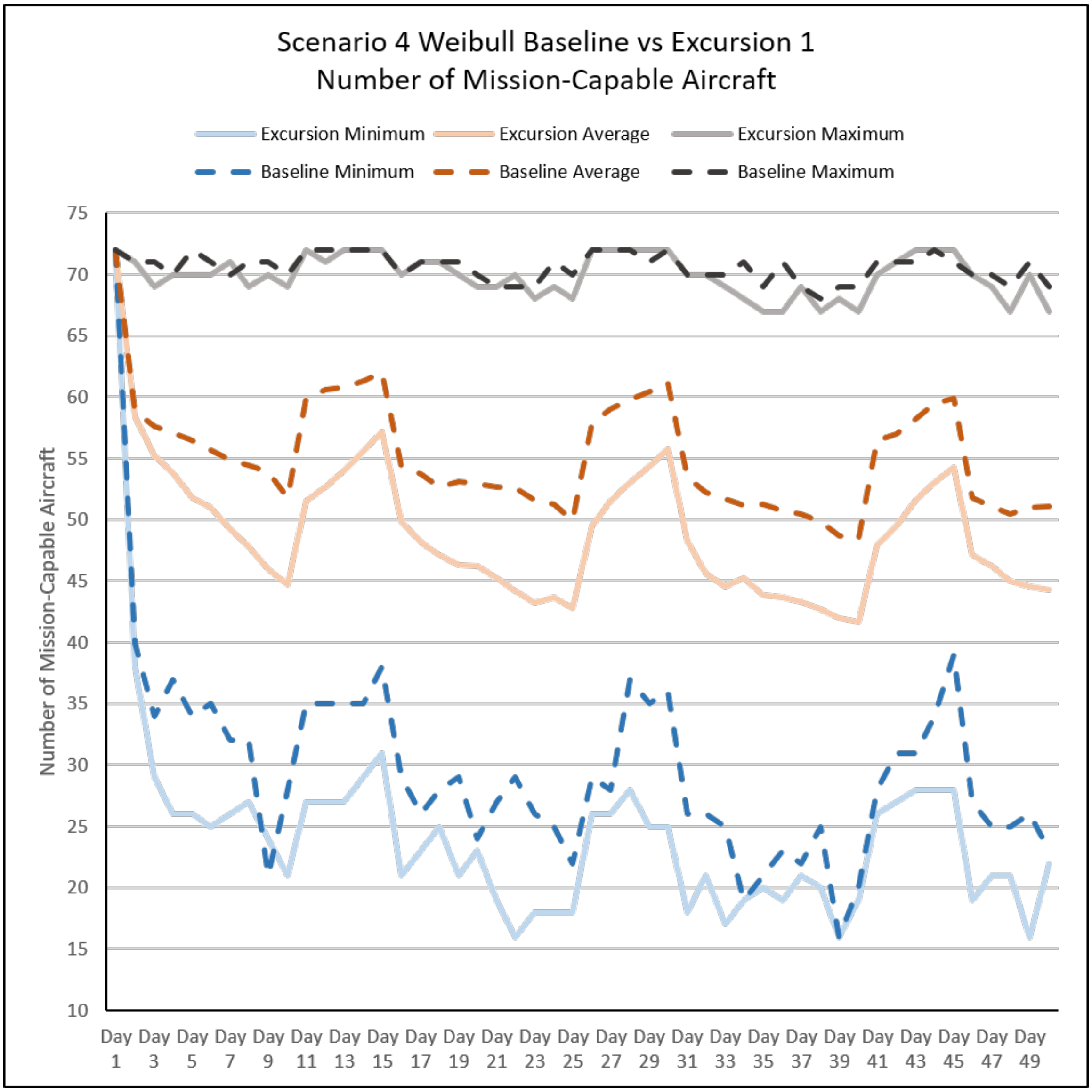


Figure 22. Scenario 4: Baseline versus Excursion 1 Number of MC Aircraft Weibull

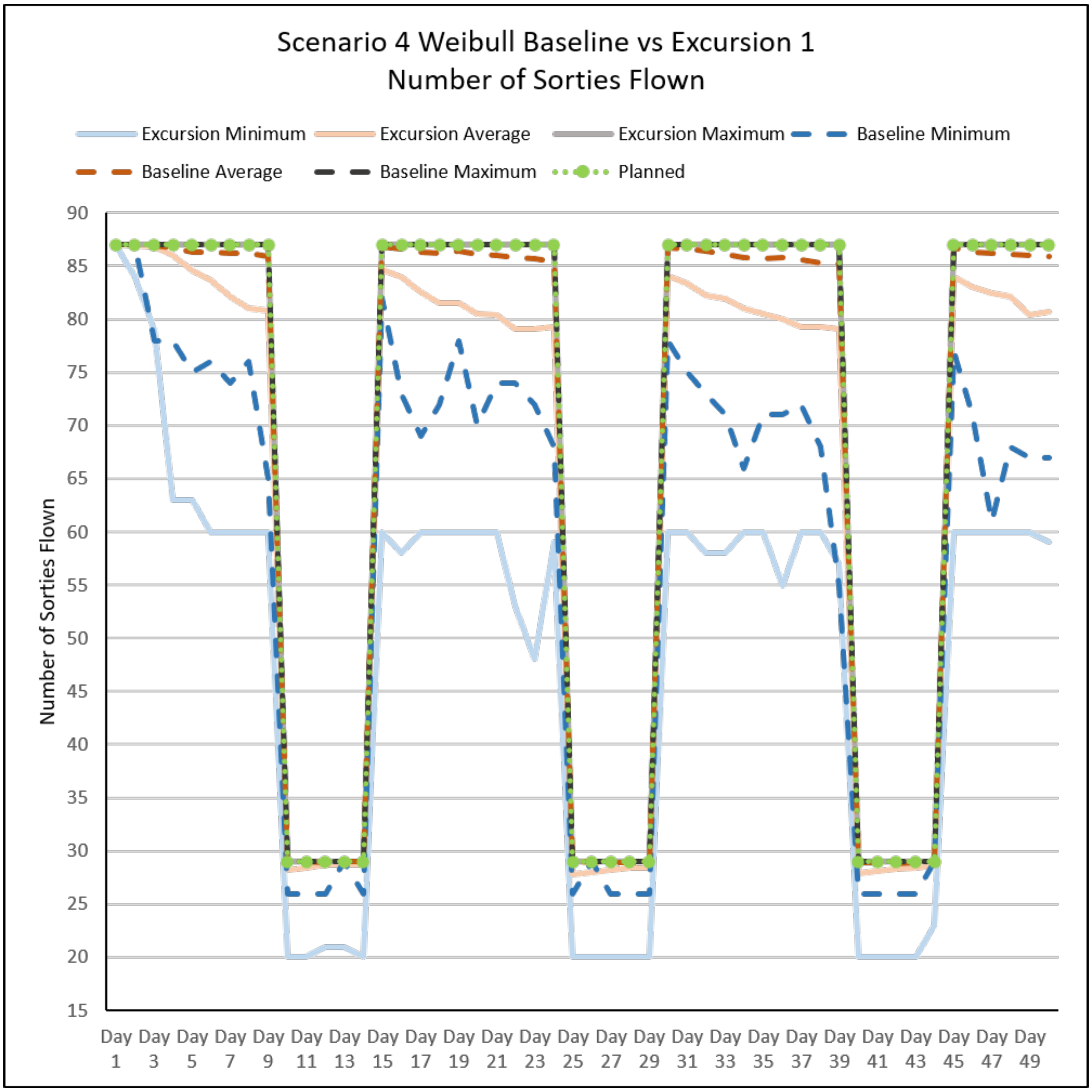


Figure 23. Scenario 4: Baseline versus Excursion 1 Number of Sorties Flown Weibull

4.4.3 Type of Aircraft

Comparing percentages by type of aircraft for the Weibull function, Table 52 shows the average percent of MC aircraft by airframe. The baseline and excursion 2 show similar percentages across all airframes except the KC-46, where the maximum personnel in excursion 2 greatly increases the percent of MC aircraft over the median level in the baseline. Excursion 1 with minimum personnel shows a large decrease in average percent MC aircraft except for F-15 and F-16. The F-15 and F-16 appear very robust with similar percentages of MC aircraft across the manning levels.

Table 52. Scenario 4: Average Percent MC Aircraft by Aircraft Weibull

Scenario 4	B-2	C-130	F-15	F-16	KC-46
Baseline	79.62%	80.52%	77.55%	77.40%	63.63%
Excursion 1	42.21%	52.57%	76.65%	77.71%	53.61%
Excursion 2	78.62%	80.00%	77.32%	78.11%	76.67%

Table 53 shows similar trends as Table 52. Comparing the two tables, the normal function appears to have slightly higher averages for the baseline and excursion 2 with the exception of the KC-46. The average for excursion 1 is much higher for the B-2 and C-130. The averages are also lower for the baseline and excursion 1 for the KC-46.

Table 53. Scenario 4: Average Percent MC Aircraft by Aircraft Normal

Scenario 4	B-2	C-130	F-15	F-16	KC-46
Baseline	81.11%	80.80%	78.66%	78.44%	62.09%
Excursion 1	48.64%	64.94%	77.00%	78.04%	50.87%
Excursion 2	79.00%	80.14%	78.74%	78.37%	76.83%

Table 54 and Table 55 show the average percent of sorties flown by aircraft for the Weibull and normal functions respectively. The baseline and excursion 2 appear very similar for both functions. Excursion 1 shows less sorties for the B-2, C-130, and KC-46 in both cases. There is not a distinct difference for the fighters. Comparing

the tables to each other, only the excursion 1 values are majorly different for the B-2, C-130, and KC-46 with the normal function showing more sorties being flown.

Table 54. Scenario 4: Average Percent Sorties Flown by Aircraft Weibull

Scenario 4	B-2	C-130	F-15	F-16	KC-46
Baseline	99.40%	99.58%	99.98%	99.99%	92.94%
Excursion 1	76.62%	87.19%	99.97%	100.00%	86.36%
Excursion 2	99.44%	99.40%	99.99%	99.98%	98.81%

Table 55. Scenario 4: Average Percent Sorties Flown by Aircraft Normal

Scenario 4	B-2	C-130	F-15	F-16	KC-46
Baseline	99.73%	99.60%	99.99%	100.00%	91.99%
Excursion 1	82.48%	94.36%	99.95%	99.99%	84.64%
Excursion 2	99.48%	99.53%	100.00%	99.98%	98.75%

Plots broken out by type of aircraft are in Figures 72, 76, 80, 84, and 88 in Appendix D.

4.4.4 Scenario 4 Insights

Scenario 4 continues to show not a lot of strain on the model as 100% of sorties are being flown for the maximum and 95% of sorties flown for the worst average. There is also large variability in the minimum MC aircraft and sorties flown as seen in Figure 22 and Figure 23.

In scenario 4, there is evidence that there is a significant difference between the normal and Weibull functions when it comes to average number of MC aircraft. The maximum and minimums showed no difference for both MC aircraft and sorties flown. The average sorties flown only showed a difference in a single excursion.

Manning levels also affect the number of MC aircraft and number of sorties flown. The minimum manning level in excursion 1 shows significantly less average and minimum MC aircraft, and average and minimum sorties flown. There is not a major difference between median and maximum manning levels.

4.4.5 Scenario 4 Excursion 3

Scenario 4, excursion 3 was added to strain the model, specifically MTBF and MTTR. The goal of this excursion was to reduce the maximum percent of sorties flown below 100%. The scenario 4 baseline was modified by doubling the number of scheduled sorties while keeping all other parameters the same. A comparison of the baseline and excursion 3 can be seen in Table 17. The results from this excursion can be seen in Table 56 through Table 59 and Figure 24 and Figure 25.

Table 56 shows there is a significant difference only in the average number of MC aircraft, agreeing with the other excursions from scenario 4. Table 57 shows there is no difference between the models for number of sorties flown.

Table 56. Scenario 4: Excursion 3 Paired T-test *P* values for Number of MC Aircraft

	Maximum *P* Value	Average *P* Value	Minimum *P* Value
Excursion 3	0.559	0.000	0.811

Table 57. Scenario 4: Excursion 3 Paired T-test *P* values for Number of Sorties Flown

	Maximum *P* Value	Average *P* Value	Minimum *P* Value
Excursion 3	0.766	0.064	0.611

Table 58 depicts the percentage of MC aircraft for both the normal and Weibull MTTR functions compared to the baseline which has half the amount of sorties scheduled. Excursion 3 has roughly 25% less MC aircraft for the maximum, about 20% less for the average, but the minimums are nearly equal.

Table 58. Scenario 4: Excursion 3 Percent MC Aircraft

	Maximum Percent MC Aircraft	Average Percent MC Aircraft	Minimum Percent MC Aircraft
Baseline Weibull	98.1%	76.5%	41.3%
Baseline Normal	98.1%	77.3%	41.8%
Excursion 3 Weibull	73.1%	57.6%	41.6%
Excursion 3 Normal	73.5%	58.1%	41.7%

Table 59 displays the percentage of sorties flown in excursion 3 compared to the baseline. Despite scheduling twice as many sorties, excursion 3 still flew about 97% of them compared to the baseline's 100%. The average percent of sorties flown differs much more. Excursion 3 flies 81% of sorties while the baseline flies 99%, an 18% difference. The difference in minimum percent sorties flown is 27%. The baseline is able to fly 85% of sorties and excursion 3 only 58% of sorties.

Table 59. Scenario 4: Excursion 3 Percent Sorties Flown

	Maximum Percent Sorties Flown	Average Percent Sorties Flown	Minimum Percent Sorties Flown
Baseline Weibull	100.00%	99.16%	84.43%
Baseline Normal	100.00%	99.10%	85.72%
Excursion 3 Weibull	96.93%	80.93%	58.19%
Excursion 3 Normal	96.80%	81.25%	58.68%

Figure 24 is a plot of the number of MC aircraft available each day of the simulation. The most interesting thing to note is the minimum number of MC aircraft remains relatively the same with both displaying large variability. Despite scheduling twice as many sorties, the excursion minimum does not show more variability than the baseline minimum. The excursion maximum number of MC aircraft is very similar to the average number of MC aircraft in the baseline. The maximum number of MC aircraft in the baseline is well above all excursion 3 values. Overall, there is much more variability in the number of MC aircraft when the number of sorties increases. This is evidenced by the fluctuating lines from the excursion in the minimum, average, and maximum values.

Figure 25 shows a plot of the number of sorties flown for the excursion and baseline. The maximum and average number of sorties flown for the excursion are well above the baseline as expected. The excursion minimum shows more variability than previous scenarios. The excursion minimum begins with more sorties flown than the baseline maximum the first 16 days. Then the excursion minimum varies between the baseline maximum and baseline minimum the next 10 days. Looking at day 30, the excursion

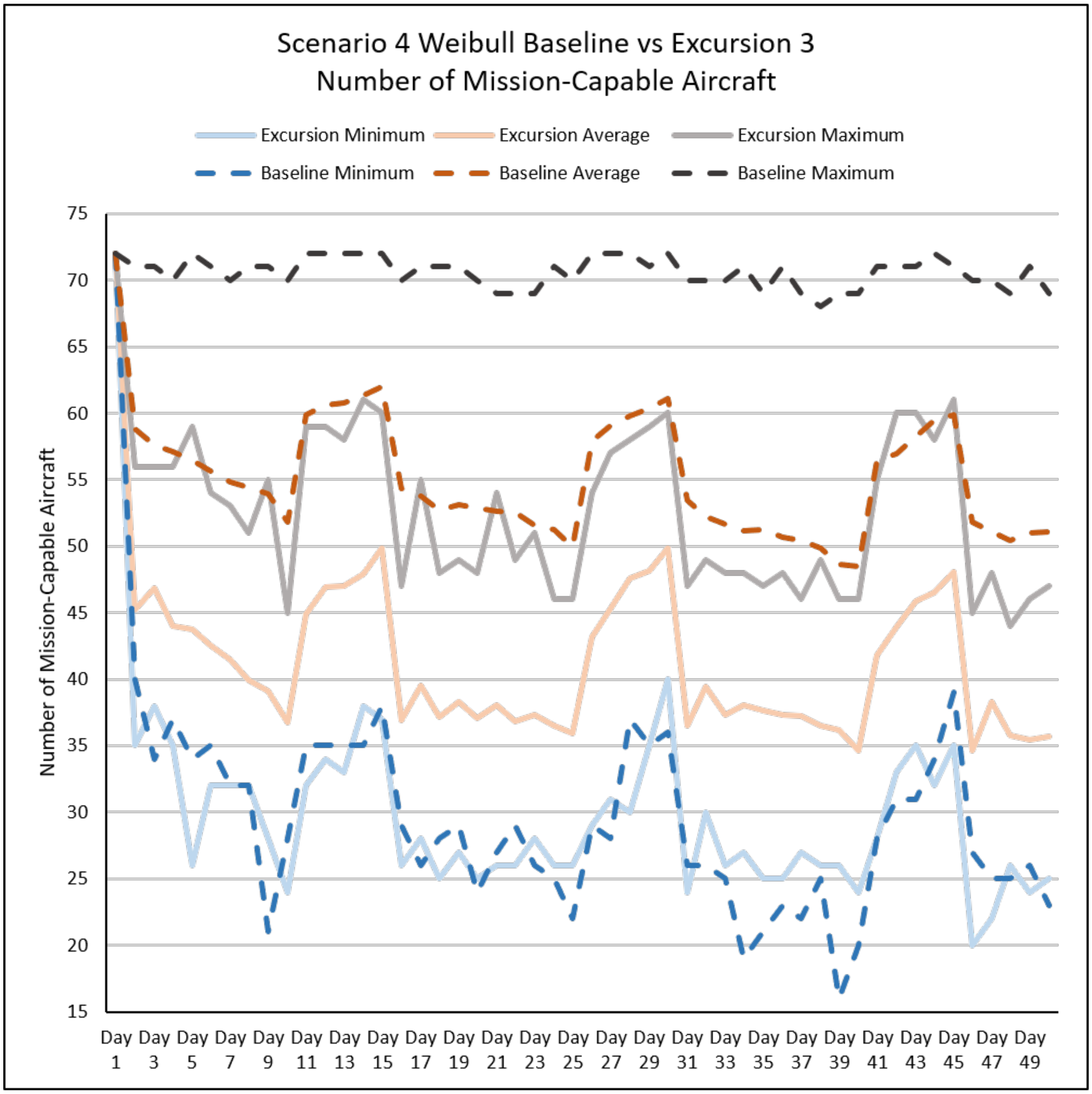


Figure 24. Scenario 4: Baseline versus Excursion 3 Number of MC Aircraft Weibull

minimum is very close to the baseline maximum, then on day 45 it drops well below the baseline maximum. Again this shows there is much more variability in the minimum, along with average, and maximum number of sorties flown for the excursion.

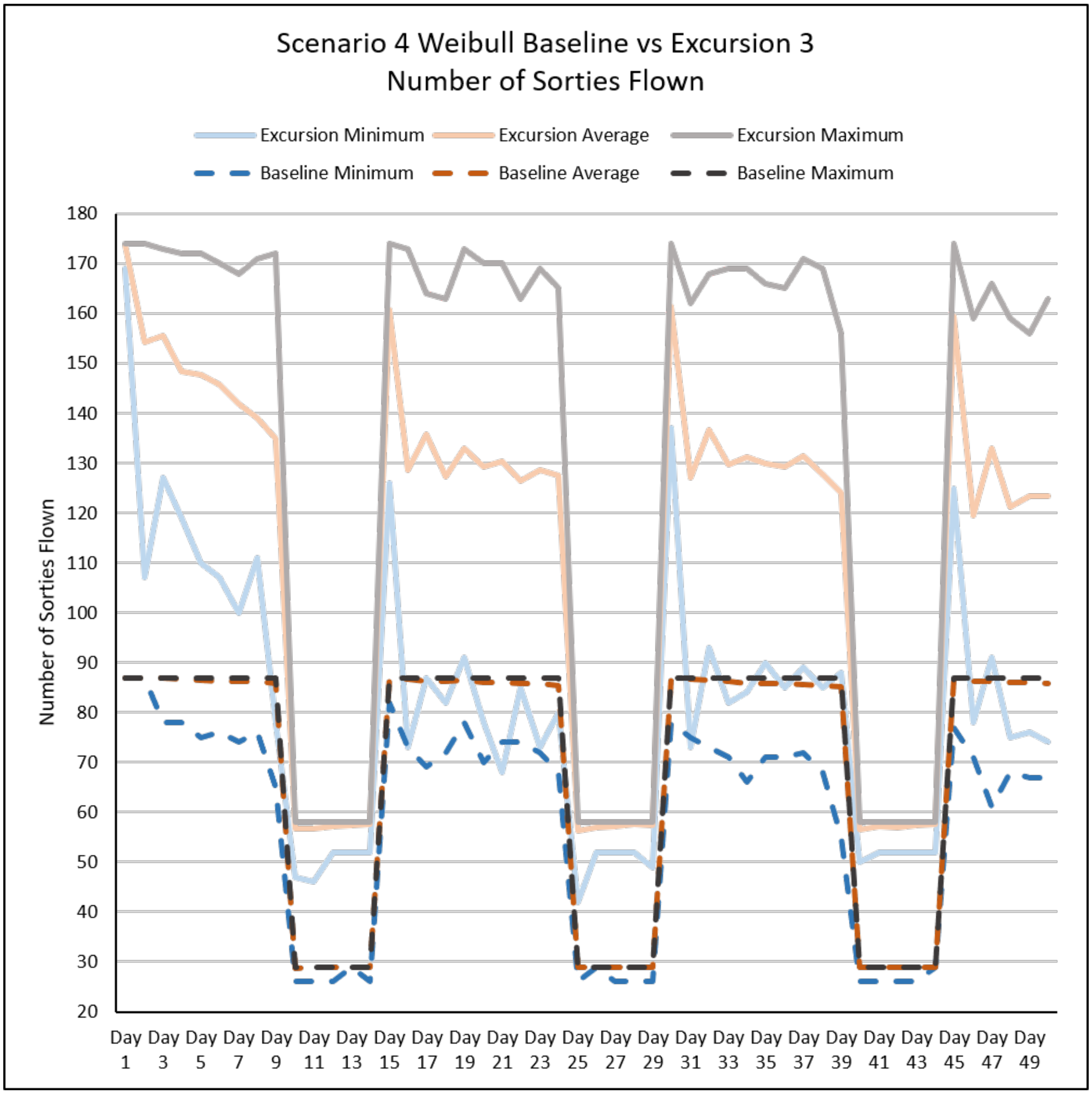


Figure 25. Scenario 4: Baseline versus Excursion 3 Number of Sorties Flown Weibull

4.4.6 Scenario 4 Excursion 3 Insights

From excursion 3, it is evident that flying more sorties results in lower MC rates. These MC rates do not change linearly. The maximum decreased 25%, the average 20%, and the minimum 0%. Flying more sorties also results in more variability in MC aircraft and sorties accomplished. The number of sorties flown does not impact minimum number of MC aircraft. This excursion is able to stress the upper limit on sortie generation to see the affect maintenance personnel have on this upper limit. Flying more sorties results in fewer MC aircraft. The further sorties are increased, the greater amount of aircraft breaks occur. This results in fewer MC aircraft having to fly the same number of scheduled sorties which causes additional breaks in the remaining MC aircraft. This cyclical nature is detrimental to the number of MC aircraft. However, it appears there is a minimum threshold of MC aircraft, that no matter the sortie demand, maintenance is able to provide a certain number of MC aircraft given the manning level remains the same. For example, in Figure 24, the baseline and excursion 3 have differing sortie demands but are always able to provide about 25 MC aircraft for the median manning level.

4.5 Expected Number of In-Game Mission-capable Aircraft Model Efficiency

The efficiency of the enhanced ENIGMA model is compared to the previous ENIGMA model via run times. It was previously known the number of sorties flown directly affects simulation run time; more sorties equates to longer run times. For this reason, the scenario 2 baseline run times are measured since scenario 2's baseline has the most sorties scheduled. Table 60 displays the recorded run times. The same computer is used for each run; the computer processor is an Intel Xeon E5-2699 v3 with 2.30 GHz and 6.00 GB of RAM. The new ENIGMA model with the normal

MTTR function took about 7 minutes longer than the previous version of ENIGMA. The new ENIGMA model with the Weibull MTTR function took about 8 minutes longer than the previous version of ENIGMA. Overall, the new ENIGMA version requires 10% to 11% more time to run depending on the distribution used. The Weibull MTTR function takes about 1% longer to run than the normal MTTR function.

Table 60. Run time comparison between versions of ENIGMA

	Normal MTTR Function	**Weibull MTTR Function**
New ENIGMA	70.8 min	71.8 min
Previous ENIGMA	63.6 min	

V. Conclusions and Recommendations

There are four major insights gained from this research, answering the questions posed in Chapter 1.

1.) Adequate models are developed representing MTTR as a function of available maintenance personnel.

2.) The MTTR models are validated for use in ENIGMA.

3.) A statistical significant difference exists between the MTTR functions which use normal and Weibull distributions for the assumption of residual error fit when determining MC aircraft. These statistical differences do not appear to manifest into large operational differences in output.

4.) Operational insights are gained into the affect of maintenance personnel on aircraft sortie generation.

   a. There is large variability in the minimum number of MC aircraft and minimum number of sorties flown.

   b. Scenarios 1 through 3 do not stress the limits of MTBF and MTTR as evidenced by the 100% of sorties scheduled able to be flown.

   c. Below median manning levels result in reduced numbers of MC aircraft and sorties flown, while above median manning levels provide no significant improvements to MC aircraft or sorties flown.

   d. Operating at one base versus two bases results in more sorties flown, but fewer MC aircraft.

Each of these insights will be discussed in detail with a focus on operational insights.

5.1 Conclusions

It is possible to develop adequate models to represent MTTR as a function of available maintenance personnel. This is evidenced by Table 1 where at least 77% of model variance is accounted for in each of the developed models.

It is also possible to validate the MTTR models. Plots of maintenance personnel level by MTTR prove MTTR exponentially decays as maintenance personnel increases.

There is a difference between the normal and Weibull functions for average number of MC aircraft. This is evidenced by Table 18, Table 28, Table 38, and Table 46. In scenario 1, three out of the four excursions had a statistically significant difference between the average number of MC aircraft. Scenario 2 had no significant differences, but in scenarios 3 and 4, all excursions had a significant difference in average number of MC aircraft. The minimum and maximum numbers of MC aircraft had 2 each excursions across all scenarios that were significantly different. Number of sorties flown did not show a pattern in significant differences. This leads to a statistical difference between the normal and Weibull functions, but only for average number of MC aircraft. This difference in average number of MC aircraft is due to skewness in the Weibull model. For the normal model, the mean MTTR equals the median MTTR, but in the Weibull model, the mean MTTR is longer than the median MTTR. This slightly longer MTTR in the Weibull model shows a trend of slightly lower percentages of MC aircraft, causing the difference between the models. However, this small difference in percentage of MC aircraft is not great enough to cause a significant difference in percentage of sorties flown.

Large low-end variability exists in both MC aircraft and sorties flown across all scenarios. Factors affecting this variability include MTBF and MTTR. However, in scenario 4, excursion 3, there is more variability in the average and maximum number

of MC aircraft and sorties flown. This indicates that sorties scheduled also affects this variability. As more sorties are flown, more aircraft are likely to break causing variability in MC aircraft, which in turn affects the number of sorties able to be flown. The lack of variability in scenarios 1 through 3 in the averages and maximums show the system is not being stressed as maintenance is able to keep up with repairs.

As already mentioned, scenarios 1 through 3 did not stress the limits of MTBF and MTTR. This is shown by the 100% of sorties flown and 99% MC rates throughout all these scenarios. This makes it difficult to determine the true affect maintenance personnel have on sortie generation. To strain the model, scenario 4, excursion 3 was added, doubling the number of sorties from scenario 4's baseline. This reduced the maximum percent of sorties flown to about 97%. Doubling the number of sorties results in a 25% reduction in maximum and average percent of MC aircraft. Most interesting is there was no change in minimum number of MC aircraft. This means number of sorties does not affect the minimum number of MC aircraft, but does affect the maximum and average.

A conclusion can also be made about manning levels and how they affect MC aircraft and sorties flown. Generally, less personnel results in less MC aircraft and fewer sorties. In scenario 1, this can be seen in Figure 10 and Figure 11 where the excursion has less average and minimum MC aircraft and sorties flown the first 15 days of the simulation which has reduced personnel. This can also be seen in scenario 4 in Figure 22 and Figure 23. Again, the excursion with minimum personnel has less average and minimum MC aircraft and sorties flown compared to the baseline with median personnel. There is not a large difference between median and maximum personnel levels. Operating with below median levels of maintenance personnel will result in reduced MC aircraft and sorties flown. Operating between median and maximum levels of personnel will not result in a significant increase of MC aircraft

and sorties flown.

In scenario 2, when comparing operations at one base to two bases with the same number of personnel and aircraft, the two-base excursion has a higher percentage of maximum and average MC aircraft, but a much lower percentage of minimum MC aircraft. When comparing percent sorties flown, the single base flies more sorties on average and nearly 10% more for the minimum sorties flown. The conclusion is that more sorties being flown is more of a priority than higher numbers of MC aircraft. This makes excursion 2, operating at a single base, more effective since more missions are able to be accomplished.

This thesis provides the enhancement of ENIGMA as a capability to provide insight into sortie generation for wargaming and exercises. The enhanced ENIGMA simulation provides the impact of evolving operational scenarios to include how available maintenance personnel affect sortie generation. ENIGMA is greatly enhanced in providing the impact of available maintenance personnel on meeting sortie demands and understanding its influence on mission accomplishment.

5.2 Recommendations

The Recommendations section is broken into two categories. The first category is recommendations for maintenance manpower. The second is recommendations for future research.

5.2.1 Recommendations for Maintenance Manning

When calculating required maintenance personnel levels, it is recommended that maintenance manning levels be near the median level. There are no major differences between the median and maximum levels. However, there is a great difference between the median and minimum levels. Reducing the manning level below median may

result in reduced numbers of MC aircraft and sorties flown. This recommendation is based on LCOM outputs being representative of actual performance.

It is also recommended to deploy at least the median maintenance manning level as soon as possible. Slowly increasing the number of personnel resulted in reduced numbers of MC aircraft and sorties flown until a more complete compliment of personnel was available. Shortening the length of arrivals of personnel will result in more MC aircraft and sorties flown during the beginning stages of operations.

Lastly, it is recommended to operate at a single base rather multiple bases, if the number of personnel and aircraft remain the same. It was shown that operating at a single base results in more sorties flown, although fewer MC aircraft.

5.2.2 Recommendations for Future Work

For future research, the MTTR function can be adjusted to use a random number from a Weibull or normal distribution instead of the expected value. Parameters for both the Weibull and normal distributions for each aircraft are provided. Implementing these distributions into the MTTR functions in ENIGMA would allow for a random number to be generated, accounting for more of the variation in real-world repair times. Another aspect would be to recreate the MTTR functions with operational data instead of LCOM data.

Appendix A. Regression Model Prediction Expressions

B-2 Weibull Equation

$$\begin{aligned} MTTR = exp(3.03011224956196 + -0.0381288399382462 * 2A0S1+ \\ (2A0S1 - 10.0384615384615) * ((2A0S1 - 10.0384615384615)* \\ 0.00790145874796269)) * gamma(1 + 0.137072608822572) \end{aligned} \tag{8}$$

B-2 Normal Equation

$$\begin{aligned} MTTR = 18.5249753822334 + -0.53672220206441 * 2A0S1+ \\ (2A0S1 - 10.0384615384615) * ((2A0S1 - 10.0384615384615) * 0.131460335030658) \end{aligned} \tag{9}$$

C-130 Weibull Equation

$$\begin{aligned} MTTR = exp(3.3741147016534 + -0.0103588349981702 * 2A5F1 + -0.0100699966317414 * 2A5R1+ \\ - 0.0188357945051237 * 2A6F1 + -0.0192999003372329 * 2A6F5 + -0.0193481951740229 * 2A6F6+ \\ - 0.00767906885892463 * 2A8F1 + -0.0157404727349896 * 2A8F2 + 0.0125559722365042 * 2P6S4+ \\ (2A5F1 - 26.0307692307692) * ((2A5F1 - 26.0307692307692) * 0.000649772015555436)+ \\ (2A6F1 - 9.50769230769231) * ((2A6F1 - 9.50769230769231) * 0.00434363946234993)+ \\ (2A5F1 - 26.0307692307692) * ((2A6F6 - 7.50769230769231) * -0.000491068478479582)+ \\ (2A6F6 - 7.50769230769231) * ((2A6F6 - 7.50769230769231) * 0.00428935174670223)+ \\ (2A8F1 - 8.00769230769231) * ((2A8F1 - 8.00769230769231) * 0.00295626158520881)+ \\ (2A8F2 - 5.50384615384615) * ((2A8F2 - 5.50384615384615) * 0.0056867876618264))* \\ gamma(1 + 0.0655291287424111) \end{aligned} \tag{10}$$

C-130 Normal Equation

$$\begin{aligned} MTTR = 26.3486599720381 + -0.181149275490032 * 2A5F1 + -0.143983870942609 * 2A5R1+ \\ - 0.360720159328411 * 2A6F1 + -0.26896476729217 * 2A6F5 + -0.32090205331248 * 2A6F6+ \\ - 0.105598054217488 * 2A8F1 + -0.271679939323459 * 2A8F2 + 0.20694233633006 * 2P6S4+ \\ (2A5F1 - 26.0307692307692) * ((2A5F1 - 26.0307692307692) * 0.0124021739001826)+ \\ (2A6F1 - 9.50769230769231) * ((2A6F1 - 9.50769230769231) * 0.0531554069318041)+ \\ (2A5F1 - 26.0307692307692) * ((2A6F6 - 7.50769230769231) * -0.00520860633268796)+ \\ (2A6F6 - 7.50769230769231) * ((2A6F6 - 7.50769230769231) * 0.0710595512654939)+ \\ (2A8F1 - 8.00769230769231) * ((2A8F1 - 8.00769230769231) * 0.0365310326493043)+ \\ (2A8F2 - 5.50384615384615) * ((2A8F2 - 5.50384615384615) * 0.0494455443443591) \end{aligned} \tag{11}$$

F-15 Weibull Equation

$$MTTR = exp(1.07563007845335 + -0.0000346737170293824 * 2A3X3 + -0.000342642594453034 * 2A3X4B+$$
$$- 0.0000706559550300112 * 2A0X1S + 0.00123894785537629 * 2A3W3 + 0.00171399921871187 * 2A6T1+$$
$$0.00112211717318489 * 2A6S6 + -0.00205534307074023 * 2A7S1 + 0.000552310146855645 * 2A7S2+$$
$$- 0.0013734591225661 * 2A7X3 + (2A0X1S - 8.36434108527132) * ((2A0X1S - 8.36434108527132) * 0.000257232830677565)+$$
$$(2A3X3 - 31.1046511627907) * ((2A3W3 - 3.70542635658915) * 0.00016400194440438)+$$
$$(2A3X4B - 21.562015503876) * ((2A3W3 - 3.70542635658915) * -0.000371160375253517)+$$
$$(2A6T1 - 2.4031007751938) * ((2A6T1 - 2.4031007751938) * 0.00381315292520837)+$$
$$(2A6T1 - 2.4031007751938) * ((2A6S6 - 4.81395348837209) * 0.00137173915610668)+$$
$$(2A6T1 - 2.4031007751938) * ((2A7S1 - 6.0077519379845) * -0.00185956761047316)+$$
$$(2A7S1 - 6.0077519379845) * ((2A7S1 - 6.0077519379845) * 0.000643193858225034)+$$
$$(2A3X4B - 21.562015503876) * ((2A7S2 - 6.01162790697674) * 0.000314964780422893)+$$
$$(2A7S1 - 6.0077519379845) * ((2A7S2 - 6.01162790697674) * -0.00103435591308697)+$$
$$(2A7S1 - 6.0077519379845) * ((2A7X3 - 11.968992248062) * 0.000554102298839234)) * gamma(1 + 0.0162759835107932) \quad (12)$$

F-15 Normal Equation

$$MTTR = 2.90688844861632 + -0.000134988140844186 * 2A3X3 + -0.000948838234913117 * 2A3X4B+$$
$$- 0.0000211252536920504 * 2A0X1S + 0.00147812574453214 * 2A3W3 + 0.005162479696718 * 2A6T1+$$
$$0.00174782621129755 * 2A6S6 + -0.00461562984157384 * 2A7S1 + 0.00137651878207652 * 2A7S2+$$
$$- 0.00225156155639808 * 2A7X3 + (2A0X1S - 8.36434108527132) * ((2A0X1S - 8.36434108527132) * 0.00052118308411118)+$$
$$(2A3X3 - 31.1046511627907) * ((2A3W3 - 3.70542635658915) * 0.000497644674226226)+$$
$$(2A3X4B - 21.562015503876) * ((2A3W3 - 3.70542635658915) * -0.00090080043354754)+$$
$$(2A6T1 - 2.4031007751938) * ((2A6T1 - 2.4031007751938) * 0.00715983939585715)+$$
$$(2A6T1 - 2.4031007751938) * ((2A6S6 - 4.81395348837209) * 0.00245828534565287)+$$
$$(2A6T1 - 2.4031007751938) * ((2A7S1 - 6.0077519379845) * -0.00308988669960589)+$$
$$(2A7S1 - 6.0077519379845) * ((2A7S1 - 6.0077519379845) * 0.00172325665535348)+$$
$$(2A3X4B - 21.562015503876) * ((2A7S2 - 6.01162790697674) * 0.000878118974280689)+$$
$$(2A7S1 - 6.0077519379845) * ((2A7S2 - 6.01162790697674) * -0.00272499564283497)+$$
$$(2A7S1 - 6.0077519379845) * ((2A7X3 - 11.968992248062) * 0.000838934626048849) \quad (13)$$

F-16 Weibull Equation

$$MTTR = exp(1.30519045321307 + 0.00551274619820105 * 2A0X1K + 0.00273785419542577 * 2A3P3+$$
$$- 0.000867478839351486 * 2A3X3 + -0.00357132377912812 * 2A3X4 + 0.00903595711189449 * 2A6S6+$$
$$- 0.00455422793246412 * 2A6X1 + 0.00211213698464099 * 2A6X4 + 0.018869372604447 * 2A6X5+$$
$$- 0.00977694026760332 * 2A6X6 + -0.00759217397667968 * 2A7X1 + -0.00148492494895612 * 2A7X3+$$

$$0.000710739417301921*2W1L1+-0.0102975079794112*2W1S1+0.00312314466692382*2W1X1+$$
$$(2A3X4-9.68503937007874)*((2A3X4-9.68503937007874)*0.00103083279085242)+$$
$$(2A6S6-3.76377952755905)*((2A6S6-3.76377952755905)*-0.00646952754033229)+$$
$$(2A3X3-25.488188976378)*((2A6X1-7.2992125984252)*0.000148669975709631)+$$
$$(2A3X4-9.68503937007874)*((2A6X1-7.2992125984252)*-0.00142286306029019)+$$
$$(2A6X1-7.2992125984252)*((2A6X1-7.2992125984252)*0.00134582685109538)+$$
$$(2A3X4-9.68503937007874)*((2A6X4-6.18897637795276)*0.00113090366480989)+$$
$$(2A3X4-9.68503937007874)*((2A6X6-7.31496062992126)*-0.000640318899642622)+$$
$$(2A7X1-3.74803149606299)*((2A7X1-3.74803149606299)*0.00708261797169496)+$$
$$(2A0X1K-2.69291338582677)*((2A7X3-9.74803149606299)*-0.00390736552147916)+$$
$$(2A6X5-2.7007874015748)*(2A7X3-9.74803149606299)*-0.00311516762502941)+$$
$$(2A6X6-7.31496062992126)*((2A7X3-9.74803149606299)*0.000820766167539177)+$$
$$(2W1L1-21.9370078740157)*((2W1L1-21.9370078740157)*-0.0000457254272438789)+$$
$$(2A7X3-9.74803149606299)*((2W1S1-4.88976377952756)*0.00150080951130995)+$$
$$(2A3P3-13.3937007874016)*((2W1X1-5.45669291338583)*-0.00108943502448191)+$$
$$(2A3X4-9.68503937007874)*((2W1X1-5.45669291338583)*-0.00116043663413558)+$$
$$(2A6S6-3.76377952755905)*((2W1X1-5.45669291338583)*0.000375963067650269))*gamma(1+0.0315943939306148) \tag{14}$$

F-16 Normal Equation

$$MTTR=3.47420458982199+0.0192424211997102*2A0X1K+0.0102996317733495*2A3P3+$$
$$-0.00380677872677874*2A3X3+-0.00753932169567626*2A3X4+0.0298394347229809*2A6S6+$$
$$-0.0173236725856476*2A6X1+0.0127322867956215*2A6X4+0.0815505044718973*2A6X5+$$
$$-0.0345025866811269*2A6X6+-0.0150655738208181*2A7X1+-0.00192157198478166*2A7X3+$$
$$0.00280903354930399*2W1L1+-0.0361428129596577*2W1S1+0.0166280698736455*2W1X1+$$
$$(2A3X4-9.68503937007874)*((2A3X4-9.68503937007874)*0.00356667672814015)+$$
$$(2A6S6-3.76377952755905)*((2A6S6-3.76377952755905)*-0.0241330649753593)+$$
$$(2A3X3-25.488188976378)*((2A6X1-7.2992125984252)*0.000530502148519301)+$$
$$(2A3X4-9.68503937007874)*((2A6X1-7.2992125984252)*-0.00499088430019001)+$$
$$(2A6X1-7.2992125984252)*((2A6X1-7.2992125984252)*0.00482078889785412)+$$
$$(2A3X4-9.68503937007874)*((2A6X4-6.18897637795276)*0.00420748764347168)+$$
$$(2A3X4-9.68503937007874)*((2A6X6-7.31496062992126)*-0.00273299311736264)+$$
$$(2A7X1-3.74803149606299)*((2A7X1-3.74803149606299)*0.0196810042769427)+$$
$$(2A0X1K-2.69291338582677)*((2A7X3-9.74803149606299)*-0.014221398252994)+$$
$$(2A6X5-2.7007874015748)*((2A7X3-9.74803149606299)*-0.0119487955017109)+$$
$$(2A6X6-7.31496062992126)*((2A7X3-9.74803149606299)*0.00206493592313451)+$$
$$(2W1L1-21.9370078740157)*((2W1L1-21.9370078740157)*-0.00029372689429355)+$$
$$(2A7X3-9.74803149606299)*((2W1S1-4.88976377952756)*0.00464267411432848)+$$
$$(2A3P3-13.3937007874016)*((2W1X1-5.45669291338583)*-0.00477488068235047)+$$
$$(2A3X4-9.68503937007874)*((2W1X1-5.45669291338583)*-0.00547421698227778)+$$
$$(2A6S6-3.76377952755905)*((2W1X1-5.45669291338583)*0.0057710549844469) \tag{15}$$

KC-46 Weibull Equation

$$\begin{aligned}MTTR = exp(&3.56791330725468 + -0.0877115597950558 * 2A5X1 + -0.0106825873531001 * 2A5X3A+\\&0.00281248490377276 * 2A5X3B + 0.0305616180276256 * 2A5X3C + -0.0222385880004829 * 2A6X5+\\&- 0.00881398866049667 * 2A6X6 + 0.0120134593362839 * 2A7X1 + (2A5X1 - 7.47222222222222)*\\&((2A5X1 - 7.47222222222222) * 0.0318360587036799) + (2A5X1 - 7.47222222222222)*\\&((2A5X3B - 3.5) * 0.0224294971111506) + (2A5X3A - 2.5) * ((2A5X3C - 3.5) * 0.0401464975575238)+\\&(2A5X3B - 3.5) * ((2A5X3C - 3.5) * 0.0443872209129977) + (2A5X3A - 2.5) * ((2A6X5 - 3.5) * -0.0295677088681236)+\\&(2A6X5 - 3.5) * ((2A6X6 - 5) * 0.0146524194859876)) * gamma(1 + 0.00875583578536215)\end{aligned} \tag{16}$$

KC-46 Normal Equation

$$\begin{aligned}MTTR = &31.0215605129992 + -1.75531836117655 * 2A5X1 + -0.125857833479742 * 2A5X3A+\\&0.119362368894414 * 2A5X3B + 0.615345682085638 * 2A5X3C + -0.427638097009087 * 2A6X5+\\&- 0.190276527213736 * 2A6X6 + 0.199447685994265 * 2A7X1 + (2A5X1 - 7.47222222222222)*\\&((2A5X1 - 7.47222222222222) * 0.764341199451354) + (2A5X1 - 7.47222222222222)*\\&((2A5X3B - 3.5) * 0.480899274884086) + (2A5X3A - 2.5) * ((2A5X3C - 3.5) * 0.530433072300832)+\\&(2A5X3B - 3.5) * ((2A5X3C - 3.5) * 0.596048780286786) + (2A5X3A - 2.5) * ((2A6X5 - 3.5) * -0.623873358534411)+\\&(2A6X5 - 3.5) * ((2A6X6 - 5) * 0.308244898015236)\end{aligned} \tag{17}$$

Appendix B. Manning Levels by Aircraft and Air Force Specialty Code

Table 61 shows the B-2 manning levels.

Table 61. B-2 Manning Levels

B-2	2A0S1
Min	2
25th pctl	6
Median	10
75th pctl	14
Max	18

Table 62 shows the C-130 manning levels.

Table 62. C-130 Manning Levels

C-130	2A5F1	2A5R1	2A6F1	2A6F5	2A6F6	2A8F1	2A8F2	2P6S4
Min	4	4	3	3	2	3	2	3
25th pctl	15	6	7	4	5	6	4	4
Median	26	7	10	5	8	8	6	5
75th pctl	37	8	13	6	11	11	8	6
Max	48	9	16	6	13	13	9	6

Table 63 shows the F-15 manning levels.

Table 63. F-15 Manning Levels

F-15	2A3X3	2A3X4B	2A0X1S	2A3W3	2A6T1	2A6S6	2A7S1	2A7S2	2A7X3
Min	4	3	2	2	1	2	2	2	2
25th pctl	23	16	7	4	3	5	6	6	9
Median	41	29	12	6	4	7	9	9	16
75th pctl	60	42	17	8	5	10	12	12	23
Max	78	54	21	9	6	12	15	15	30

Table 64 shows the F-16 manning levels.

Table 64. F-16 Manning Levels

F-16	2A0X1K	2A3P3	2A3X3	2A3X4	2A6S6	2A6X1	2A6X4	2A6X5	2A6X6	2A7X1	2A7X3	2W1L1	2W1S1	2W1X1
Min	2	3	4	3	2	2	3	2	2	2	2	3	2	4
25th pctl	3	11	19	9	4	6	6	3	6	4	8	16	5	6
Median	4	18	34	14	6	10	9	4	10	6	13	29	7	8
75th pctl	5	26	49	19	8	14	12	5	14	8	19	42	10	10
Max	6	33	63	24	9	18	15	6	18	9	24	54	12	12

Table 65 shows the KC-46 manning levels.

Table 65. KC-46 Manning Levels

KC-46	2A5X1	2A5X3A	2A5X3B	2A5X3C	2A6X5	2A6X6	2A7X1
Min	6	2	3	3	3	4	2
25th pctl	7	2	3	3	3	5	2
Median	8	3	4	4	4	5	3
75th pctl	8	3	4	4	4	6	3
Max	9	3	4	4	4	6	3

Appendix C. Regression Model Results by Aircraft

3.1 B-2 Regression Models

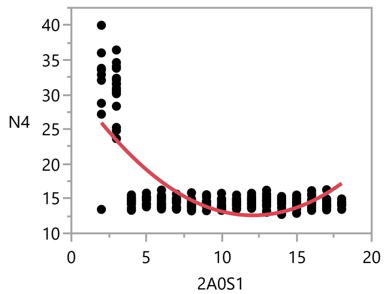
Generalized Regression for N4

Model Comparison

Show	Response Distribution	Estimation Method	Validation Method	Nonzero Parameters	AICc	BIC	R-Square
☑	Normal	Standard Least Squares	None	4	1407.2099	1421.2958	0.5093278
☑	Weibull	Maximum Likelihood	None	4	1222.6333	1236.7191	0.7724707

Standard Least Squares

Regression Plot



Model Summary

Response	N4
Distribution	Normal
Estimation Method	Standard Least Squares
Validation Method	None
Mean Model Link	Identity
Scale Model Link	Identity

Measure	
Number of rows	260
Sum of Frequencies	260
-LogLikelihood	699.52652
Number of Parameters	4
BIC	1421.2958
AICc	1407.2099
RSquare	0.5093278
RSquare Adj	0.5055094
RASE	3.5663693

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	18.524975	0.5819473	1013.3231	<.0001*	17.38438	19.665571
2A0S1	-0.536722	0.047515	127.5962	<.0001*	-0.62985	-0.443595
(2A0S1-10.0385)*(2A0S1-10.0385)	0.1314603	0.0112046	137.65676	<.0001*	0.1094997	0.1534209

Normal Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	3.5871243	0.158685	511	<.0001*	3.2761074	3.8981413

Generalized Regression for N4

Standard Least Squares

Effect Tests

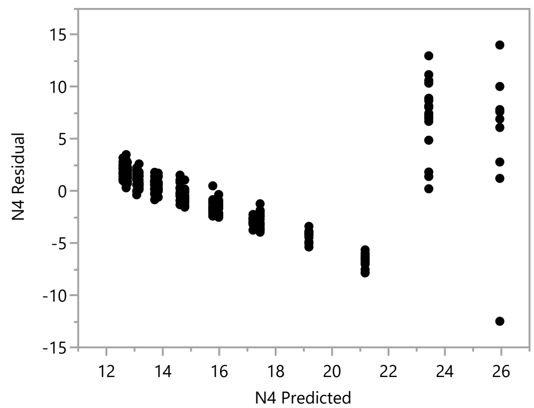
Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
2A0S1*2A0S1	1	1	1771.293	137.65676	<.0001*
2A0S1	1	1	1641.8391	127.5962	<.0001*

Prediction Expression

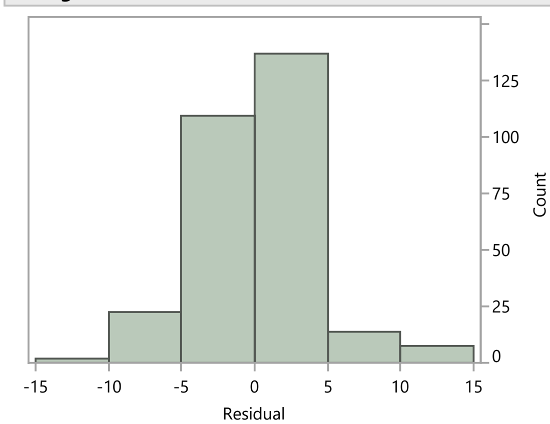
$$18.524975382$$
$$+ -0.536722202 \cdot 2A0S1$$
$$+ \left(2A0S1 - 10.038461538\right) \cdot \left(\left(2A0S1 - 10.038461538\right) \cdot 0.131460335\right)$$

Diagnostic Bundle

Residual by Predicted Plot



Histogram of Residuals

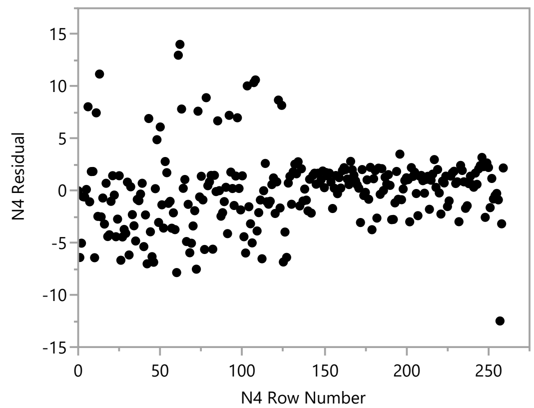


Generalized Regression for N4

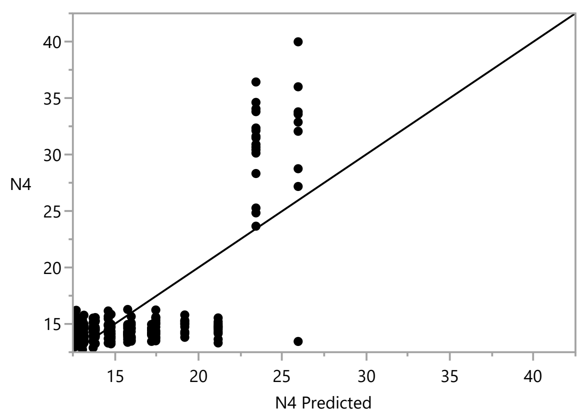
Standard Least Squares

Diagnostic Bundle

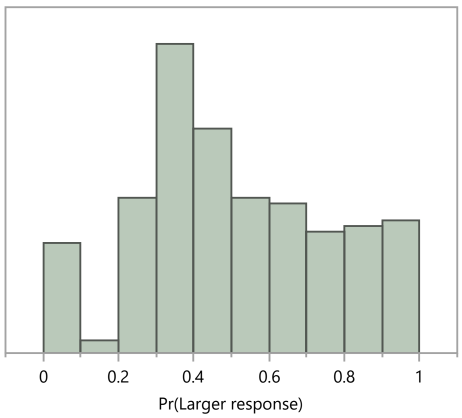
Residual by Row Plot



Actual by Predicted Plot



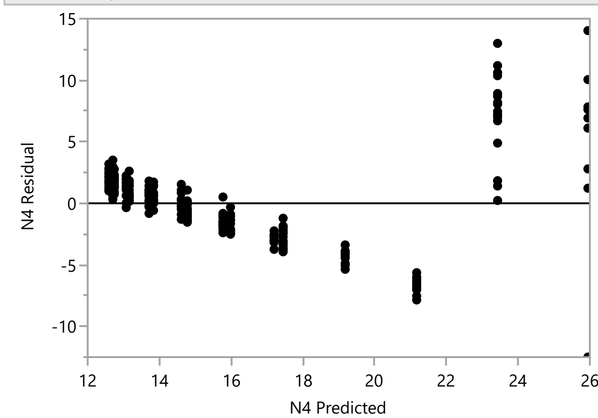
Fitted Probability of Observing a Larger Response



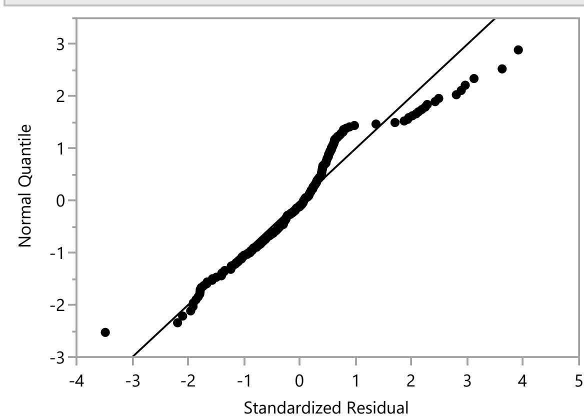
Generalized Regression for N4

Standard Least Squares

Residual by Predicted Plot



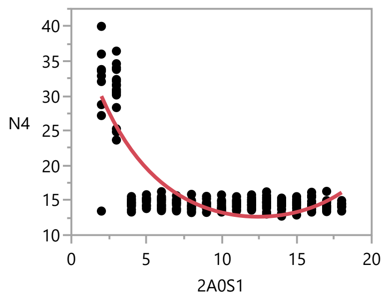
Normal Quantile Plot



Generalized Regression for N4

Weibull Maximum Likelihood

Regression Plot



Model Summary

Response	N4
Distribution	Weibull
Estimation Method	Maximum Likelihood
Validation Method	None
Location Model Link	Identity
Scale Model Link	Identity

Measure	
Number of rows	260
Sum of Frequencies	260
-LogLikelihood	607.23821
Number of Parameters	4
BIC	1236.7191
AICc	1222.6333
Generalized RSquare	0.7724707

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	3.0301122	0.0290001	10917.365	<.0001*	2.9732731	3.0869514
2A0S1	-0.038129	0.0021072	327.42306	<.0001*	-0.042259	-0.033999
(2A0S1-10.0385)*(2A0S1-10.0385)	0.0079015	0.0004553	301.23453	<.0001*	0.0070092	0.0087937

Weibull Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	0.1370726	0.006838	401.83618	<.0001*	0.1236705	0.1504748

Effect Tests

Source	Nparm	DF	Wald ChiSquare	Prob > ChiSquare
2A0S1	1	1	327.42306	<.0001*
2A0S1*2A0S1	1	1	301.23453	<.0001*

Generalized Regression for N4

Weibull Maximum Likelihood

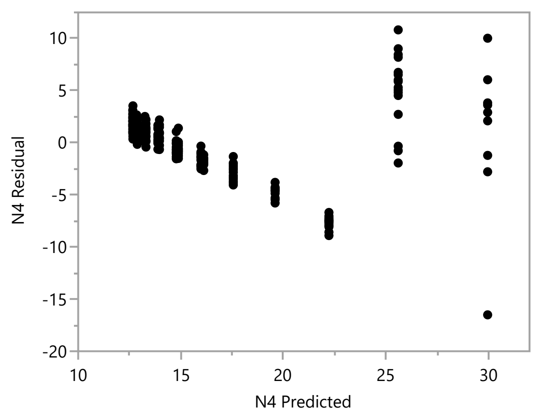
Prediction Expression

$$\mathrm{Exp}\left(\begin{array}{l}3.0301122496 \\ + -0.03812884 \cdot \mathrm{2A0S1} \\ + \left(\mathrm{2A0S1} - 10.038461538\right) \cdot \left(\left(\mathrm{2A0S1} - 10.038461538\right) \cdot 0.0079014587\right)\end{array}\right)$$

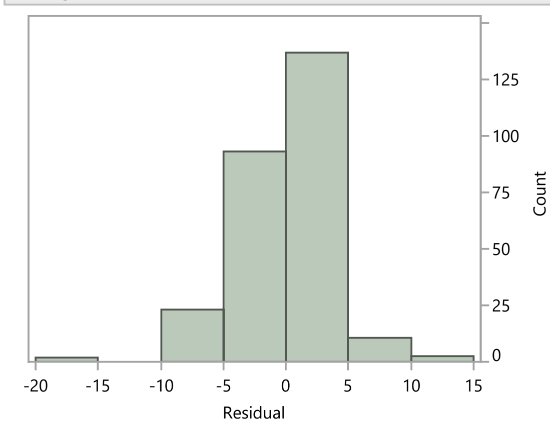
$$\cdot\,\mathrm{Gamma}\left(1 + 0.1370726088\right)$$

Diagnostic Bundle

Residual by Predicted Plot



Histogram of Residuals

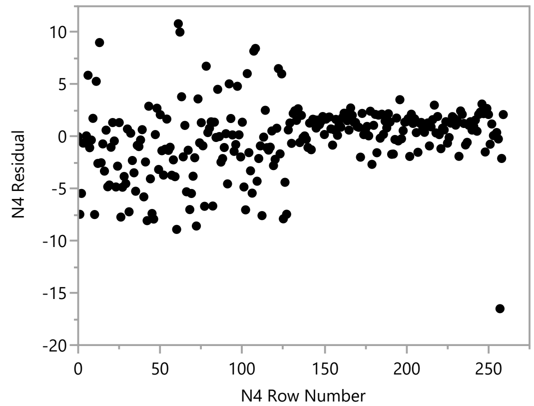


Generalized Regression for N4

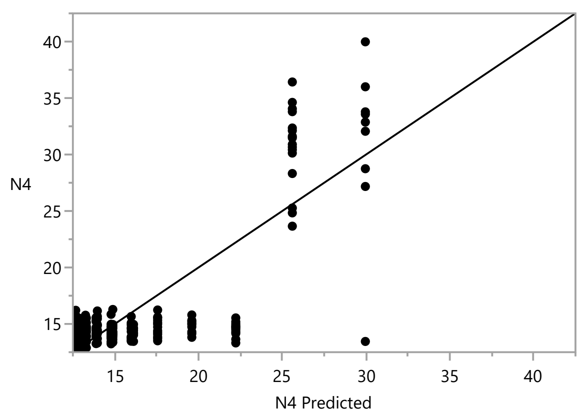
Weibull Maximum Likelihood

Diagnostic Bundle

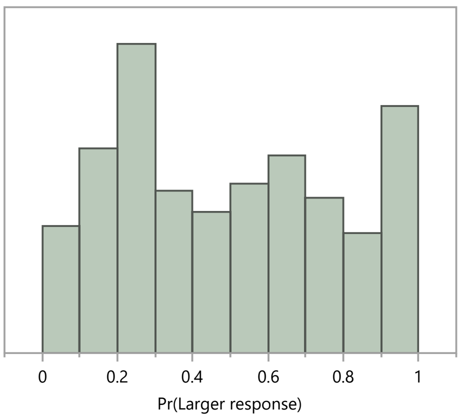
Residual by Row Plot



Actual by Predicted Plot



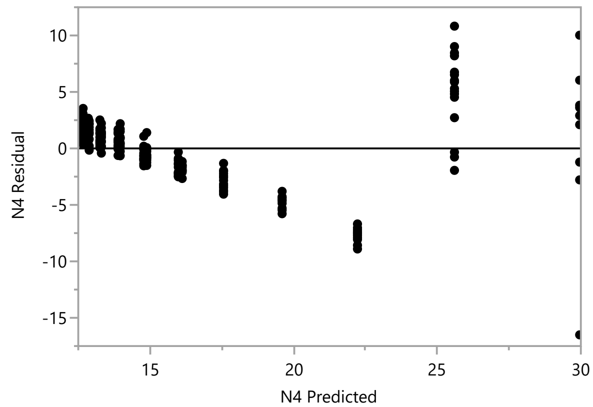
Fitted Probability of Observing a Larger Response



Generalized Regression for N4

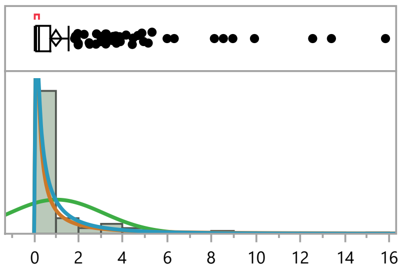
Weibull Maximum Likelihood

Residual by Predicted Plot



Distributions

Studentized Resid N4^2



Compare Distributions

Distribution		AICc	AICc Weight	.2 .4 .6 .8	BIC	-2*LogLikelihood
Weibull		259.94374	1		267.01841	255.89705
Lognormal		313.73583	0		320.8105	309.68914
Normal		1131.5397	0		1138.6144	1127.493

Quantiles

100.0%	maximum	15.827544612
99.5%		15.084539763
97.5%		8.3124238322
90.0%		3.2494249255
75.0%	quartile	0.7424579339
50.0%	median	0.2210827682
25.0%	quartile	0.0626820511
10.0%		0.0088311962
2.5%		0.0015055037
0.5%		5.768277e-7
0.0%	minimum	1.2101873e-7

Summary Statistics

Mean	1.0069934
Std Dev	2.1196274
Std Err Mean	0.1314537
Upper 95% Mean	1.2658475
Lower 95% Mean	0.7481392
N	260

Fitted Normal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Location	μ	1.0069934	0.1314537	0.7493488	1.2646379
Dispersion	σ	2.1196274	0.0640301	1.9977735	2.135344

Measures	
-2*LogLikelihood	1127.493
AICc	1131.5397
BIC	1138.6144

Distributions

Studentized Resid N4^2

Fitted Lognormal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	μ	-1.710811	0.1506325	-2.007139	-1.414483
Shape	σ	2.4288759	0.1065133	2.2341749	2.6535897

Measures	
-2*LogLikelihood	309.68914
AICc	313.73583
BIC	320.8105

Fitted Weibull Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	α	0.5240059	0.0652221	0.4093294	0.6679499
Shape	β	0.5253926	0.0247312	0.4779455	0.5748784

Measures	
-2*LogLikelihood	255.89705
AICc	259.94374
BIC	267.01841

3.2 C-130 Regression Models

Generalized Regression for N5

Model Comparison

Show	Response Distribution	Estimation Method	Validation Method	Nonzero Parameters	AICc	BIC	R-Square
☑	Weibull	Maximum Likelihood	None	16	854.37309	909.10532	0.9243998
☑	Normal	Standard Least Squares	None	16	892.96877	947.70099	0.9019136

Weibull Maximum Likelihood

Model Summary

Response	N5
Distribution	Weibull
Estimation Method	Maximum Likelihood
Validation Method	None
Location Model Link	Identity
Scale Model Link	Identity

Measure	
Number of rows	260
Sum of Frequencies	260
-LogLikelihood	410.0672
Number of Parameters	16
BIC	909.10532
AICc	854.37309
Generalized RSquare	0.9243998

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	3.3741147	0.0445594	5733.7926	<.0001*	3.28678	3.4614494
2A5F1	-0.010359	0.0003877	714.00297	<.0001*	-0.011119	-0.009599
2A5R1	-0.01007	0.0028684	12.324745	0.0004*	-0.015692	-0.004448
2A6F1	-0.018836	0.0011527	267.01892	<.0001*	-0.021095	-0.016577
2A6F5	-0.0193	0.0045006	18.389634	<.0001*	-0.028121	-0.010479
2A6F6	-0.019348	0.0013263	212.81951	<.0001*	-0.021948	-0.016749
2A8F1	-0.007679	0.0014337	28.689675	<.0001*	-0.010489	-0.004869
2A8F2	-0.01574	0.0020212	60.649981	<.0001*	-0.019702	-0.011779
2P6S4	0.012556	0.0043198	8.4484253	0.0037*	0.0040893	0.0210226
(2A5F1-26.0308)*(2A5F1-26.0308)	0.0006498	3.4325e-5	358.33698	<.0001*	0.0005825	0.000717
(2A6F1-9.50769)*(2A6F1-9.50769)	0.0043436	0.0003647	141.88809	<.0001*	0.0036289	0.0050583
(2A5F1-26.0308)*(2A6F6-7.50769)	-0.000491	0.0001203	16.66119	<.0001*	-0.000727	-0.000255
(2A6F6-7.50769)*(2A6F6-7.50769)	0.0042894	0.0004721	82.554894	<.0001*	0.0033641	0.0052146
(2A8F1-8.00769)*(2A8F1-8.00769)	0.0029563	0.0005245	31.769601	<.0001*	0.0019283	0.0039842
(2A8F2-5.50385)*(2A8F2-5.50385)	0.0056868	0.0011575	24.136711	<.0001*	0.0034181	0.0079555

Weibull Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	0.0655291	0.0030861	450.88139	<.0001*	0.0594806	0.0715777

Generalized Regression for N5

Weibull Maximum Likelihood

Effect Tests

Source	Nparm	DF	Wald ChiSquare	Prob > ChiSquare
2A5F1	1	1	714.00297	<.0001*
2A5F1*2A5F1	1	1	358.33698	<.0001*
2A6F1	1	1	267.01892	<.0001*
2A6F6	1	1	212.81951	<.0001*
2A6F1*2A6F1	1	1	141.88809	<.0001*
2A6F6*2A6F6	1	1	82.554894	<.0001*
2A8F2	1	1	60.649981	<.0001*
2A8F1*2A8F1	1	1	31.769601	<.0001*
2A8F1	1	1	28.689675	<.0001*
2A8F2*2A8F2	1	1	24.136711	<.0001*
2A6F5	1	1	18.389634	<.0001*
2A5F1*2A6F6	1	1	16.66119	<.0001*
2A5R1	1	1	12.324745	0.0004*
2P6S4	1	1	8.4484253	0.0037*

Generalized Regression for N5

Weibull Maximum Likelihood

Prediction Expression

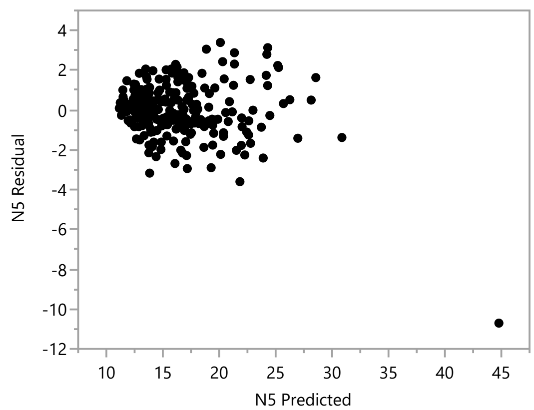
$$
\mathrm{Exp}\left(\begin{array}{l}
3.3741147017 \\
+ -0.010358835 \cdot \mathrm{2A5F1} \\
+ -0.010069997 \cdot \mathrm{2A5R1} \\
+ -0.018835795 \cdot \mathrm{2A6F1} \\
+ -0.0192999 \cdot \mathrm{2A6F5} \\
+ -0.019348195 \cdot \mathrm{2A6F6} \\
+ -0.007679069 \cdot \mathrm{2A8F1} \\
+ -0.015740473 \cdot \mathrm{2A8F2} \\
+ 0.0125559722 \cdot \mathrm{2P6S4} \\
+\left(\mathrm{2A5F1} - 26.030769231\right)\cdot\left(\left(\mathrm{2A5F1} - 26.030769231\right)\cdot 0.000649772\right) \\
+\left(\mathrm{2A6F1} - 9.5076923077\right)\cdot\left(\left(\mathrm{2A6F1} - 9.5076923077\right)\cdot 0.0043436395\right) \\
+\left(\mathrm{2A5F1} - 26.030769231\right)\cdot\left(\left(\mathrm{2A6F6} - 7.5076923077\right)\cdot -0.000491068\right) \\
+\left(\mathrm{2A6F6} - 7.5076923077\right)\cdot\left(\left(\mathrm{2A6F6} - 7.5076923077\right)\cdot 0.0042893517\right) \\
+\left(\mathrm{2A8F1} - 8.0076923077\right)\cdot\left(\left(\mathrm{2A8F1} - 8.0076923077\right)\cdot 0.0029562616\right) \\
+\left(\mathrm{2A8F2} - 5.5038461538\right)\cdot\left(\left(\mathrm{2A8F2} - 5.5038461538\right)\cdot 0.0056867877\right)
\end{array}\right)
\cdot \mathrm{Gamma}\left(1 + 0.0655291287\right)
$$

Generalized Regression for N5

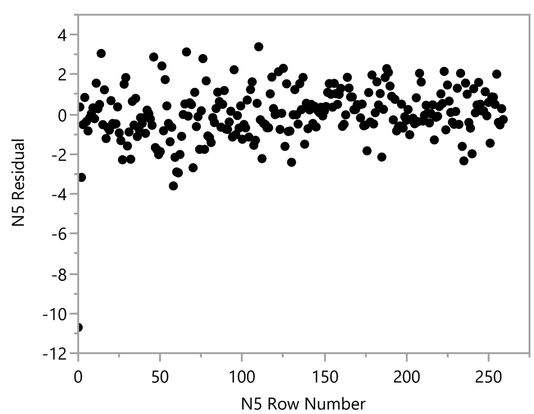
Weibull Maximum Likelihood

Diagnostic Bundle

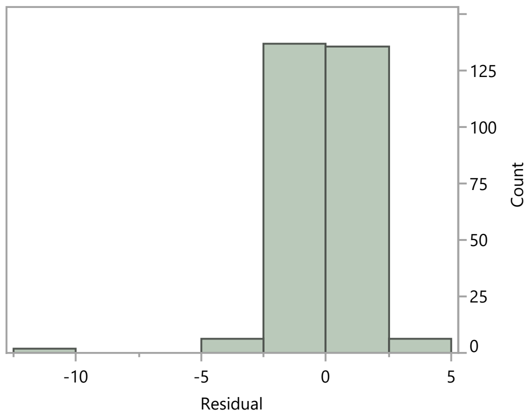
Residual by Predicted Plot



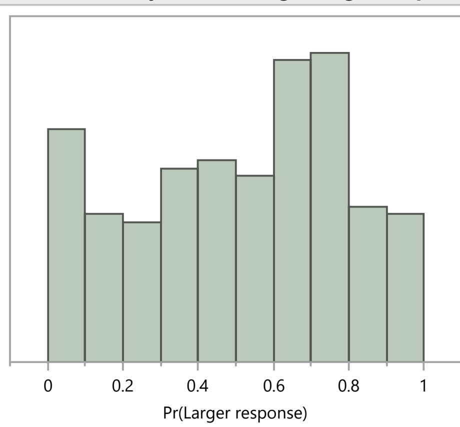
Residual by Row Plot



Histogram of Residuals



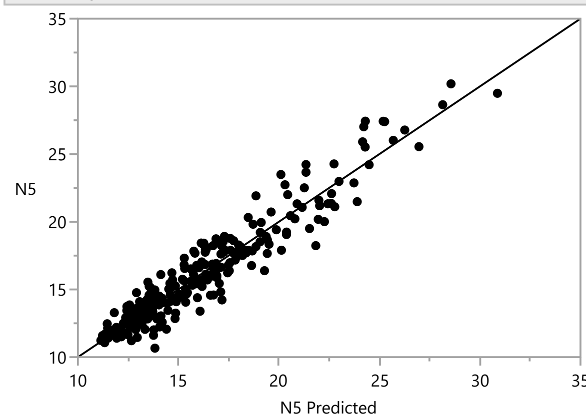
Fitted Probability of Observing a Larger Response



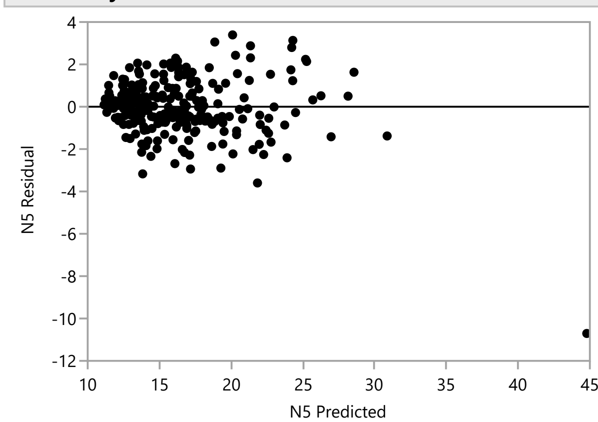
Generalized Regression for N5

Weibull Maximum Likelihood

Actual by Predicted Plot



Residual by Predicted Plot



Standard Least Squares

Model Summary

Response	N5
Distribution	Normal
Estimation Method	Standard Least Squares
Validation Method	None
Mean Model Link	Identity
Scale Model Link	Identity

Generalized Regression for N5

Standard Least Squares

Model Summary

Measure	
Number of rows	260
Sum of Frequencies	260
-LogLikelihood	429.36504
Number of Parameters	16
BIC	947.70099
AICc	892.96877
RSquare	0.9019136
RSquare Adj	0.8963086
RASE	1.2617069

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	26.34866	0.7493161	1236.4795	<.0001*	24.880027	27.817293
2A5F1	-0.181149	0.0062924	828.77439	<.0001*	-0.193482	-0.168816
2A5R1	-0.143984	0.0535194	7.2377804	0.0071*	-0.24888	-0.039088
2A6F1	-0.36072	0.0212514	288.11578	<.0001*	-0.402372	-0.319068
2A6F5	-0.268965	0.0843118	10.176871	0.0014*	-0.434213	-0.103717
2A6F6	-0.320902	0.025093	163.54609	<.0001*	-0.370083	-0.271721
2A8F1	-0.105598	0.0275016	14.743338	0.0001*	-0.1595	-0.051696
2A8F2	-0.27168	0.0388107	49.001732	<.0001*	-0.347748	-0.195612
2P6S4	0.2069423	0.0839982	6.0695878	0.0138*	0.042309	0.3715757
(2A5F1-26.0308)*(2A5F1-26.0308)	0.0124022	0.000616	405.33675	<.0001*	0.0111948	0.0136095
(2A6F1-9.50769)*(2A6F1-9.50769)	0.0531554	0.006878	59.7269	<.0001*	0.0396748	0.066636
(2A5F1-26.0308)*(2A6F6-7.50769)	-0.005209	0.0020942	6.1860151	0.0129*	-0.009313	-0.001104
(2A6F6-7.50769)*(2A6F6-7.50769)	0.0710596	0.0089288	63.337835	<.0001*	0.0535595	0.0885596
(2A8F1-8.00769)*(2A8F1-8.00769)	0.036531	0.0103353	12.493369	0.0004*	0.0162743	0.0567878
(2A8F2-5.50385)*(2A8F2-5.50385)	0.0494455	0.0207179	5.6959287	0.0170*	0.0088393	0.0900518

Normal Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	1.2997568	0.0596369	475	<.0001*	1.1828706	1.4166431

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
2A5F1	1	1	1400.1048	828.77439	<.0001*
2A5F1*2A5F1	1	1	684.76285	405.33675	<.0001*
2A6F1	1	1	486.73352	288.11578	<.0001*
2A6F6	1	1	276.28949	163.54609	<.0001*
2A6F6*2A6F6	1	1	107.0009	63.337835	<.0001*
2A6F1*2A6F1	1	1	100.9007	59.7269	<.0001*
2A8F2	1	1	82.781949	49.001732	<.0001*
2A8F1	1	1	24.906921	14.743338	0.0002*
2A8F1*2A8F1	1	1	21.105895	12.493369	0.0005*
2A6F5	1	1	17.192478	10.176871	0.0016*

Generalized Regression for N5

Standard Least Squares

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
2A5R1	1	1	12.227273	7.2377804	0.0076*
2A5F1*2A6F6	1	1	10.450455	6.1860151	0.0135*
2P6S4	1	1	10.253766	6.0695878	0.0144*
2A8F2*2A8F2	1	1	9.6225186	5.6959287	0.0178*

Prediction Expression

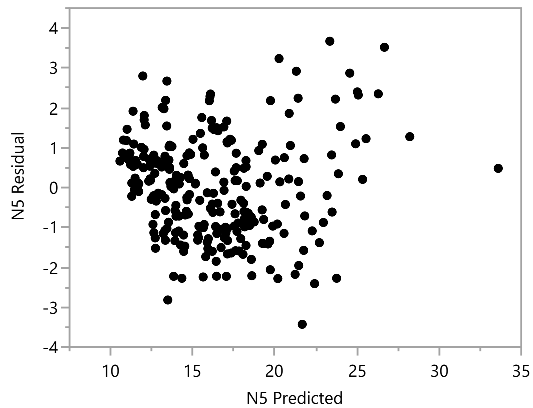
$$26.348659972$$
$$+ -0.181149275 \cdot 2A5F1$$
$$+ -0.143983871 \cdot 2A5R1$$
$$+ -0.360720159 \cdot 2A6F1$$
$$+ -0.268964767 \cdot 2A6F5$$
$$+ -0.320902053 \cdot 2A6F6$$
$$+ -0.105598054 \cdot 2A8F1$$
$$+ -0.271679939 \cdot 2A8F2$$
$$+ 0.2069423363 \cdot 2P6S4$$
$$+\left(2A5F1 - 26.030769231\right) \cdot \left(\left(2A5F1 - 26.030769231\right) \cdot 0.0124021739\right)$$
$$+\left(2A6F1 - 9.5076923077\right) \cdot \left(\left(2A6F1 - 9.5076923077\right) \cdot 0.0531554069\right)$$
$$+\left(2A5F1 - 26.030769231\right) \cdot \left(\left(2A6F6 - 7.5076923077\right) \cdot -0.005208606\right)$$
$$+\left(2A6F6 - 7.5076923077\right) \cdot \left(\left(2A6F6 - 7.5076923077\right) \cdot 0.0710595513\right)$$
$$+\left(2A8F1 - 8.0076923077\right) \cdot \left(\left(2A8F1 - 8.0076923077\right) \cdot 0.0365310326\right)$$
$$+\left(2A8F2 - 5.5038461538\right) \cdot \left(\left(2A8F2 - 5.5038461538\right) \cdot 0.0494455443\right)$$

Generalized Regression for N5

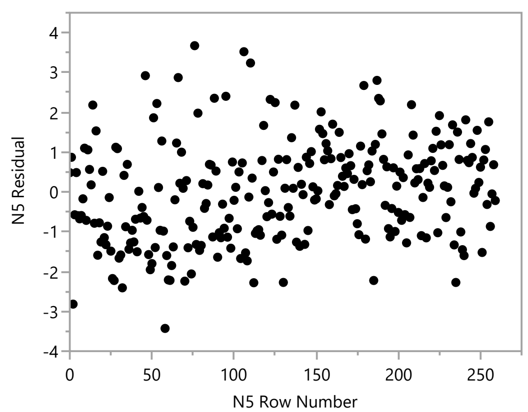
Standard Least Squares

Diagnostic Bundle

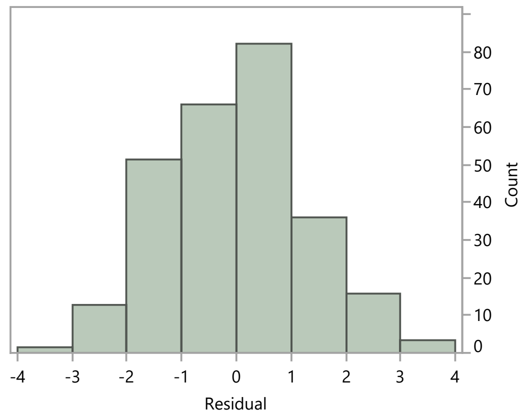
Residual by Predicted Plot



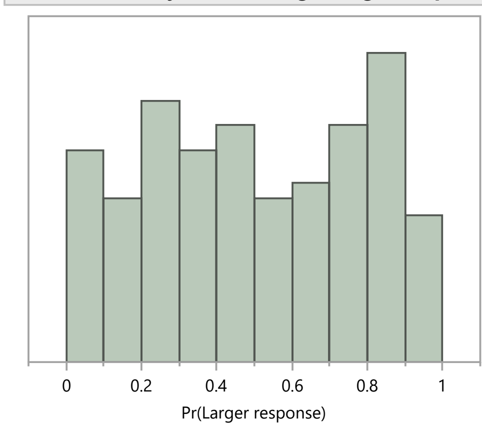
Residual by Row Plot



Histogram of Residuals



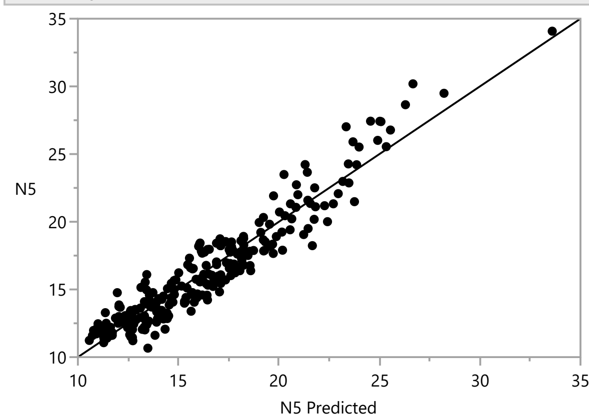
Fitted Probability of Observing a Larger Response



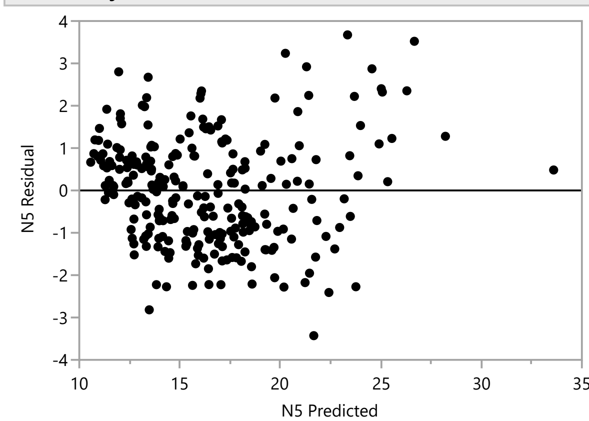
Generalized Regression for N5

Standard Least Squares

Actual by Predicted Plot



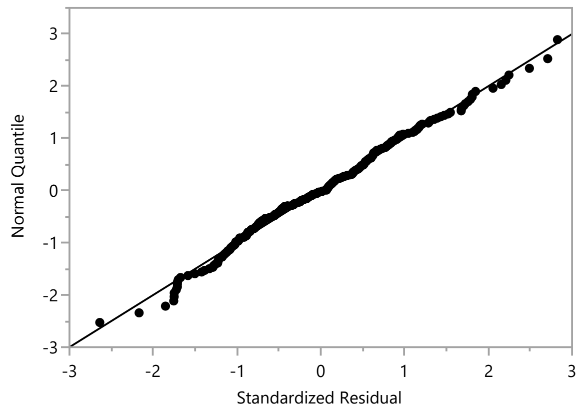
Residual by Predicted Plot



Generalized Regression for N5

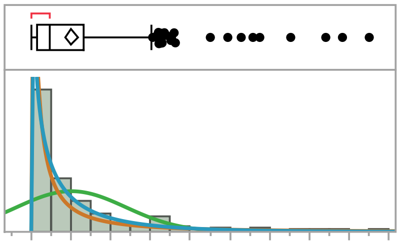
Standard Least Squares

Normal Quantile Plot



Distributions

Studentized Resid N5^2



Compare Distributions

Distribution		AICc	AICc Weight	.2 .4 .6 .8	BIC	-2*LogLikelihood
Weibull		458.18072	1		465.25539	454.13402
Lognormal		519.55715	0		526.63182	515.51046
Normal		905.6437	0		912.71837	901.59701

Quantiles

100.0%	maximum	8.5073113462
99.5%		8.3015946152
97.5%		5.4248468868
90.0%		3.0120121797
75.0%	quartile	1.3159678345
50.0%	median	0.4826830403
25.0%	quartile	0.1587287713
10.0%		0.018850347
2.5%		0.0022952908
0.5%		0.0002332336
0.0%	minimum	0.0001366275

Summary Statistics

Mean	1.006463
Std Dev	1.3727622
Std Err Mean	0.0851351
Upper 95% Mean	1.1741081
Lower 95% Mean	0.8388179
N	260

Fitted Normal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Location	μ	1.006463	0.0851351	0.8396013	1.1733248
Dispersion	σ	1.3727622	0.0515291	1.2753928	1.382941

Measures	
-2*LogLikelihood	901.59701
AICc	905.6437
BIC	912.71837

Distributions

Studentized Resid N5^2

Fitted Lognormal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	μ	-1.095722	0.1209726	-1.333702	-0.857741
Shape	σ	1.9506245	0.0855405	1.7942606	2.1310916

Measures	
-2*LogLikelihood	515.51046
AICc	519.55715
BIC	526.63182

Fitted Weibull Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	α	0.7941723	0.0751647	0.6580557	0.9551241
Shape	β	0.6883634	0.033978	0.6234159	0.7565914

Measures	
-2*LogLikelihood	454.13402
AICc	458.18072
BIC	465.25539

3.3 F-15 Regression Models

Generalized Regression for N5 (MTTR)

Model Comparison

Show	Response Distribution	Estimation Method	Validation Method	Nonzero Parameters	AICc	BIC	R-Square
☑	Weibull	Maximum Likelihood	None	21	-750.7926	-680.0957	0.7947716
☑	Normal	Standard Least Squares	None	21	-797.6214	-726.9245	0.4688412

Weibull Maximum Likelihood

Model Summary

Response	N5 (MTTR)
Distribution	Weibull
Estimation Method	Maximum Likelihood
Validation Method	None
Location Model Link	Identity
Scale Model Link	Identity

Measure	
Number of rows	261
Sum of Frequencies	258
-LogLikelihood	-398.3539
Number of Parameters	21
BIC	-680.0957
AICc	-750.7926
Generalized RSquare	0.7947716

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	1.0756301	0.0038406	78440.2	<.0001*	1.0681027	1.0831574
2A3X3	-3.467e-5	8.1778e-5	0.1797739	0.6716	-0.000195	0.0001256
2A3X4B	-0.000343	0.0001158	8.7569738	0.0031*	-0.00057	-0.000116
2A0X1S	-7.066e-5	0.0003471	0.0414293	0.8387	-0.000751	0.0006097
2A3W3	0.0012389	0.0007894	2.4633773	0.1165	-0.000308	0.0027861
2A6T1	0.001714	0.0011482	2.2282665	0.1355	-0.000536	0.0039645
2A6S6	0.0011221	0.0005698	3.8788141	0.0489*	5.4164e-6	0.0022388
2A7S1	-0.002055	0.0005136	16.015761	<.0001*	-0.003062	-0.001049
2A7S2	0.0005523	0.0004499	1.5072267	0.2196	-0.000329	0.0014341
2A7X3	-0.001373	0.0002178	39.766759	<.0001*	-0.0018	-0.000947
(2A0X1S-8.36434)*(2A0X1S-8.36434)	0.0002572	5.3728e-5	22.922365	<.0001*	0.0001519	0.0003625
(2A3X3-31.1047)*(2A3W3-3.70543)	0.000164	4.4555e-5	13.548941	0.0002*	7.6676e-5	0.0002513
(2A3X4B-21.562)*(2A3W3-3.70543)	-0.000371	6.4764e-5	32.843521	<.0001*	-0.000498	-0.000244
(2A6T1-2.4031)*(2A6T1-2.4031)	0.0038132	0.0008064	22.360085	<.0001*	0.0022326	0.0053937
(2A6T1-2.4031)*(2A6S6-4.81395)	0.0013717	0.0004858	7.9728657	0.0047*	0.0004196	0.0023239
(2A6T1-2.4031)*(2A7S1-6.00775)	-0.00186	0.0003674	25.615868	<.0001*	-0.00258	-0.001139
(2A7S1-6.00775)*(2A7S1-6.00775)	0.0006432	0.0001366	22.167635	<.0001*	0.0003754	0.0009109
(2A3X4B-21.562)*(2A7S2-6.01163)	0.000315	3.4737e-5	82.21382	<.0001*	0.0002469	0.000383
(2A7S1-6.00775)*(2A7S2-6.01163)	-0.001034	0.0001487	48.412143	<.0001*	-0.001326	-0.000743
(2A7S1-6.00775)*(2A7X3-11.969)	0.0005541	7.8333e-5	50.036469	<.0001*	0.0004006	0.0007076

Generalized Regression for N5 (MTTR)

Weibull Maximum Likelihood

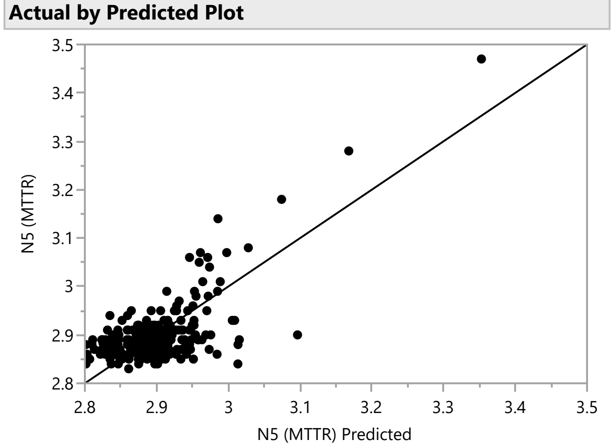
Parameter Estimates for Original Predictors

Weibull Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	0.016276	0.0007426	480.35772	<.0001*	0.0148205	0.0177315

Effect Tests

Source	Nparm	DF	Wald ChiSquare	Prob > ChiSquare
2A3X4B*2A7S2	1	1	82.21382	<.0001*
2A7S1*2A7X3	1	1	50.036469	<.0001*
2A7S1*2A7S2	1	1	48.412143	<.0001*
2A7X3	1	1	39.766759	<.0001*
2A3X4B*2A3W3	1	1	32.843521	<.0001*
2A6T1*2A7S1	1	1	25.615868	<.0001*
2A0X1S*2A0X1S	1	1	22.922365	<.0001*
2A6T1*2A6T1	1	1	22.360085	<.0001*
2A7S1*2A7S1	1	1	22.167635	<.0001*
2A7S1	1	1	16.015761	<.0001*
2A3X3*2A3W3	1	1	13.548941	0.0002*
2A3X4B	1	1	8.7569738	0.0031*
2A6T1*2A6S6	1	1	7.9728657	0.0047*
2A6S6	1	1	3.8788141	0.0489*
2A3W3	1	1	2.4633773	0.1165
2A6T1	1	1	2.2282665	0.1355
2A7S2	1	1	1.5072267	0.2196
2A3X3	1	1	0.1797739	0.6716
2A0X1S	1	1	0.0414293	0.8387

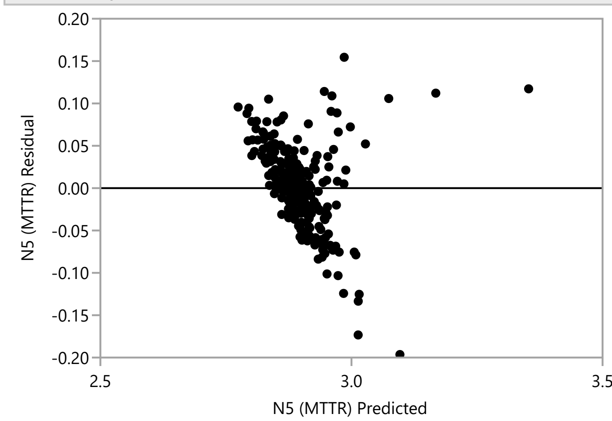
Actual by Predicted Plot



Generalized Regression for N5 (MTTR)

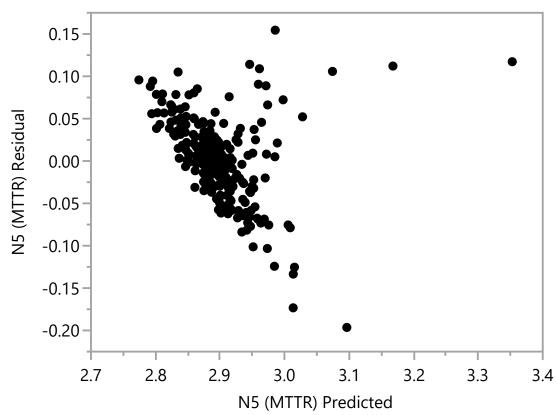
Weibull Maximum Likelihood

Residual by Predicted Plot

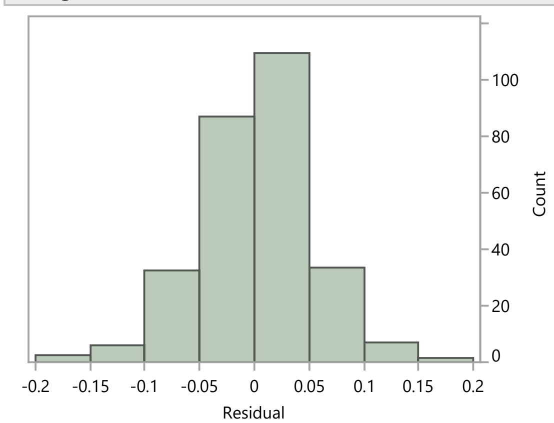


Diagnostic Bundle

Residual by Predicted Plot



Histogram of Residuals

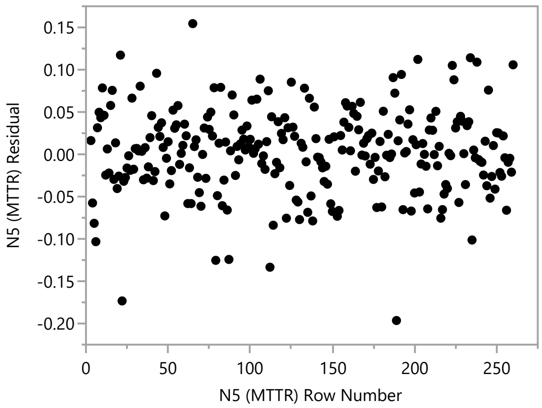


Generalized Regression for N5 (MTTR)

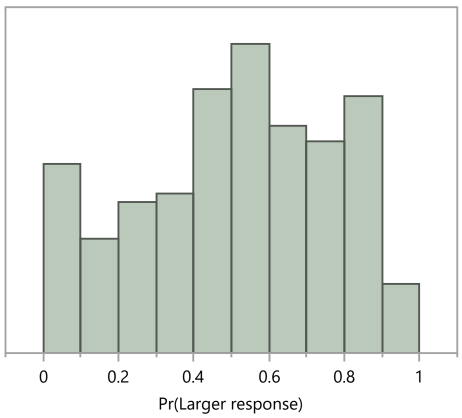
Weibull Maximum Likelihood

Diagnostic Bundle

Residual by Row Plot



Fitted Probability of Observing a Larger Response



Generalized Regression for N5 (MTTR)

Weibull Maximum Likelihood

Prediction Expression

$$\mathrm{Exp}\left(\begin{array}{l}
1.0756300785 \\
+ -0.000034674 \cdot 2A3X3 \\
+ -0.000342643 \cdot 2A3X4B \\
+ -0.000070656 \cdot 2A0X1S \\
+ 0.0012389479 \cdot 2A3W3 \\
+ 0.0017139992 \cdot 2A6T1 \\
+ 0.0011221172 \cdot 2A6S6 \\
+ -0.002055343 \cdot 2A7S1 \\
+ 0.0005523101 \cdot 2A7S2 \\
+ -0.001373459 \cdot 2A7X3 \\
+\left(2A0X1S - 8.3643410853\right)\cdot\left(\left(2A0X1S - 8.3643410853\right)\cdot 0.0002572328\right) \\
+\left(2A3X3 - 31.104651163\right)\cdot\left(\left(2A3W3 - 3.7054263566\right)\cdot 0.0001640019\right) \\
+\left(2A3X4B - 21.562015504\right)\cdot\left(\left(2A3W3 - 3.7054263566\right)\cdot -0.00037116\right) \\
+\left(2A6T1 - 2.4031007752\right)\cdot\left(\left(2A6T1 - 2.4031007752\right)\cdot 0.0038131529\right) \\
+\left(2A6T1 - 2.4031007752\right)\cdot\left(\left(2A6S6 - 4.8139534884\right)\cdot 0.0013717392\right) \\
+\left(2A6T1 - 2.4031007752\right)\cdot\left(\left(2A7S1 - 6.007751938\right)\cdot -0.001859568\right) \\
+\left(2A7S1 - 6.007751938\right)\cdot\left(\left(2A7S1 - 6.007751938\right)\cdot 0.0006431939\right) \\
+\left(2A3X4B - 21.562015504\right)\cdot\left(\left(2A7S2 - 6.011627907\right)\cdot 0.0003149648\right) \\
+\left(2A7S1 - 6.007751938\right)\cdot\left(\left(2A7S2 - 6.011627907\right)\cdot -0.001034356\right)
\end{array}\right.$$

Generalized Regression for N5 (MTTR)

Weibull Maximum Likelihood

Prediction Expression

$$\left(+\left(2A7S1 - 6.007751938 \right) \cdot \left(\left(2A7X3 - 11.968992248 \right) \cdot 0.0005541023 \right) \right)$$

$$\cdot \,\mathrm{Gamma}\left(1 + 0.0162759835 \right)$$

Standard Least Squares

Model Summary

Response	N5 (MTTR)
Distribution	Normal
Estimation Method	Standard Least Squares
Validation Method	None
Mean Model Link	Identity
Scale Model Link	Identity

Measure	
Number of rows	261
Sum of Frequencies	258
-LogLikelihood	-421.7683
Number of Parameters	21
BIC	-726.9245
AICc	-797.6214
RSquare	0.4688412
RSquare Adj	0.4264378
RASE	0.047184

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	2.9068884	0.0104439	77470.008	<.0001*	2.8864188	2.9273581
2A3X3	-0.000135	0.0002436	0.3071117	0.5795	-0.000612	0.0003424
2A3X4B	-0.000949	0.0003616	6.883525	0.0087*	-0.001658	-0.00024
2A0X1S	-2.113e-5	0.0009877	0.0004575	0.9829	-0.001957	0.0019147
2A3W3	0.0014781	0.0022725	0.4230552	0.5154	-0.002976	0.0059322
2A6T1	0.0051625	0.0031852	2.6269243	0.1051	-0.00108	0.0114053
2A6S6	0.0017478	0.0015944	1.2017627	0.2730	-0.001377	0.0048727
2A7S1	-0.004616	0.0013803	11.181145	0.0008*	-0.007321	-0.00191
2A7S2	0.0013765	0.0012648	1.1844919	0.2764	-0.001102	0.0038554
2A7X3	-0.002252	0.0006371	12.488434	0.0004*	-0.0035	-0.001003
(2A0X1S-8.36434)*(2A0X1S-8.36434)	0.0005212	0.0001579	10.89238	0.0010*	0.0002117	0.0008307
(2A3X3-31.1047)*(2A3W3-3.70543)	0.0004976	0.0001312	14.393088	0.0001*	0.0002406	0.0007547
(2A3X4B-21.562)*(2A3W3-3.70543)	-0.000901	0.0001983	20.635847	<.0001*	-0.001289	-0.000512
(2A6T1-2.4031)*(2A6T1-2.4031)	0.0071598	0.0022049	10.544898	0.0012*	0.0028384	0.0114813
(2A6T1-2.4031)*(2A6S6-4.81395)	0.0024583	0.0012187	4.0687549	0.0437*	6.9651e-5	0.0048469
(2A6T1-2.4031)*(2A7S1-6.00775)	-0.00309	0.0010594	8.5070688	0.0035*	-0.005166	-0.001014
(2A7S1-6.00775)*(2A7S1-6.00775)	0.0017233	0.0003716	21.502054	<.0001*	0.0009949	0.0024516

Generalized Regression for N5 (MTTR)

Standard Least Squares

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
(2A3X4B-21.562)*(2A7S2-6.01163)	0.0008781	0.0001191	54.4032	<.0001*	0.0006448	0.0011115
(2A7S1-6.00775)*(2A7S2-6.01163)	-0.002725	0.000436	39.063924	<.0001*	-0.00358	-0.00187
(2A7S1-6.00775)*(2A7X3-11.969)	0.0008389	0.000211	15.802075	<.0001*	0.0004253	0.0012526

Normal Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	0.0491266	0.0023006	456	<.0001*	0.0446176	0.0536356

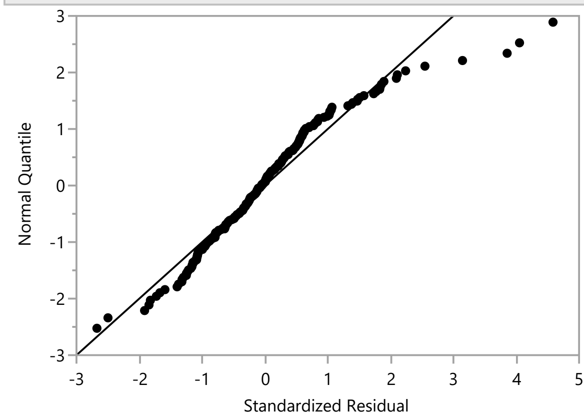
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
2A3X4B*2A7S2	1	1	0.1312978	54.4032	<.0001*
2A7S1*2A7S2	1	1	0.0942777	39.063924	<.0001*
2A7S1*2A7S1	1	1	0.0518935	21.502054	<.0001*
2A3X4B*2A3W3	1	1	0.049803	20.635847	<.0001*
2A7S1*2A7X3	1	1	0.0381371	15.802075	<.0001*
2A3X3*2A3W3	1	1	0.0347366	14.393088	0.0002*
2A7X3	1	1	0.0301398	12.488434	0.0005*
2A7S1	1	1	0.0269848	11.181145	0.0010*
2A0X1S*2A0X1S	1	1	0.0262879	10.89238	0.0011*
2A6T1*2A6T1	1	1	0.0254493	10.544898	0.0013*
2A6T1*2A7S1	1	1	0.0205311	8.5070688	0.0039*
2A3X4B	1	1	0.0166128	6.883525	0.0093*
2A6T1*2A6S6	1	1	0.0098196	4.0687549	0.0448*
2A6T1	1	1	0.0063399	2.6269243	0.1064
2A6S6	1	1	0.0029004	1.2017627	0.2741
2A7S2	1	1	0.0028587	1.1844919	0.2775
2A3W3	1	1	0.001021	0.4230552	0.5160
2A3X3	1	1	0.0007412	0.3071117	0.5800
2A0X1S	1	1	1.1041e-6	0.0004575	0.9830

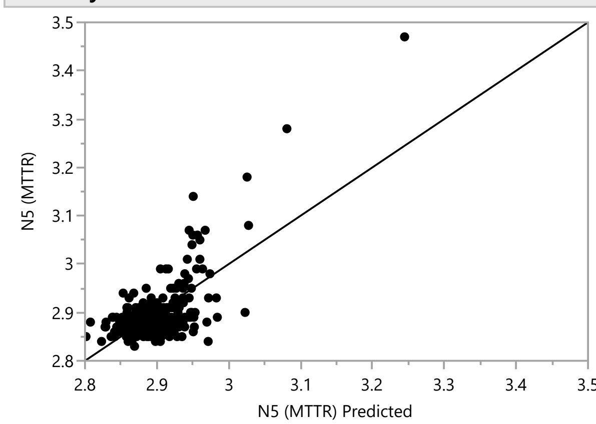
Generalized Regression for N5 (MTTR)

Standard Least Squares

Normal Quantile Plot



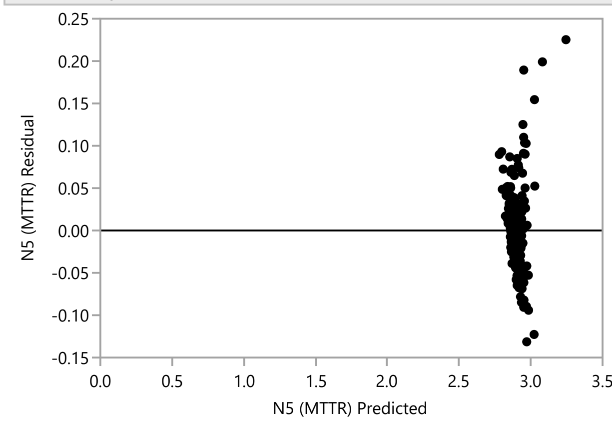
Actual by Predicted Plot



Generalized Regression for N5 (MTTR)

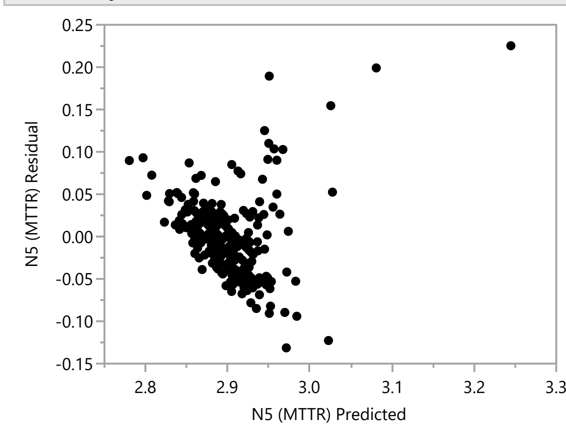
Standard Least Squares

Residual by Predicted Plot

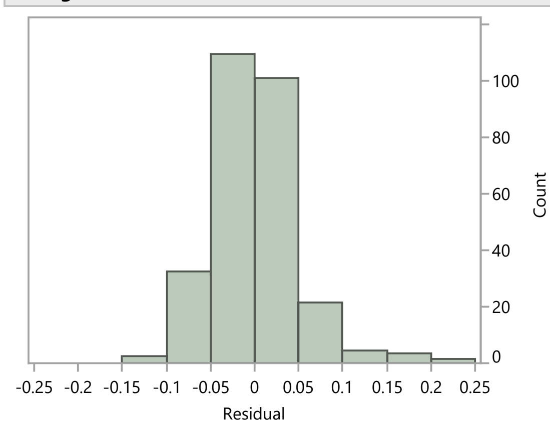


Diagnostic Bundle

Residual by Predicted Plot



Histogram of Residuals

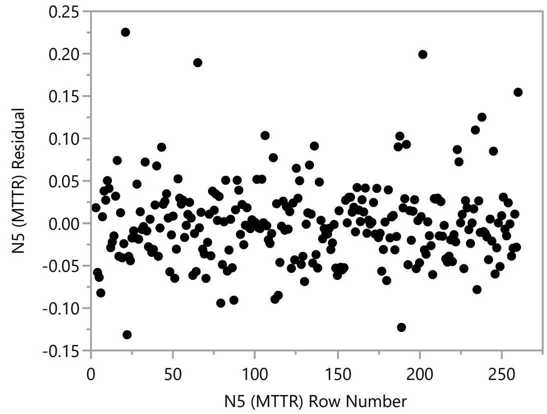


Generalized Regression for N5 (MTTR)

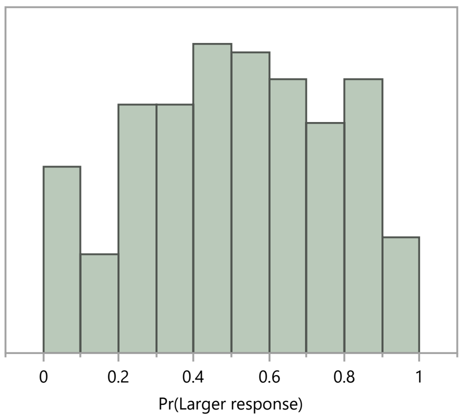
Standard Least Squares

Diagnostic Bundle

Residual by Row Plot



Fitted Probability of Observing a Larger Response



Generalized Regression for N5 (MTTR)

Standard Least Squares

Prediction Expression

$$
\begin{aligned}
&2.9068884486 \\
&+ -0.000134988 \cdot 2A3X3 \\
&+ -0.000948838 \cdot 2A3X4B \\
&+ -2.112525e\text{-}5 \cdot 2A0X1S \\
&+ 0.0014781257 \cdot 2A3W3 \\
&+ 0.0051624797 \cdot 2A6T1 \\
&+ 0.0017478262 \cdot 2A6S6 \\
&+ -0.00461563 \cdot 2A7S1 \\
&+ 0.0013765188 \cdot 2A7S2 \\
&+ -0.002251562 \cdot 2A7X3 \\
&+ \left(2A0X1S - 8.3643410853\right) \cdot \left(\left(2A0X1S - 8.3643410853\right) \cdot 0.0005211831\right) \\
&+ \left(2A3X3 - 31.104651163\right) \cdot \left(\left(2A3W3 - 3.7054263566\right) \cdot 0.0004976447\right) \\
&+ \left(2A3X4B - 21.562015504\right) \cdot \left(\left(2A3W3 - 3.7054263566\right) \cdot -0.0009008\right) \\
&+ \left(2A6T1 - 2.4031007752\right) \cdot \left(\left(2A6T1 - 2.4031007752\right) \cdot 0.0071598394\right) \\
&+ \left(2A6T1 - 2.4031007752\right) \cdot \left(\left(2A6S6 - 4.8139534884\right) \cdot 0.0024582853\right) \\
&+ \left(2A6T1 - 2.4031007752\right) \cdot \left(\left(2A7S1 - 6.007751938\right) \cdot -0.003089887\right) \\
&+ \left(2A7S1 - 6.007751938\right) \cdot \left(\left(2A7S1 - 6.007751938\right) \cdot 0.0017232567\right) \\
&+ \left(2A3X4B - 21.562015504\right) \cdot \left(\left(2A7S2 - 6.011627907\right) \cdot 0.000878119\right) \\
&+ \left(2A7S1 - 6.007751938\right) \cdot \left(\left(2A7S2 - 6.011627907\right) \cdot -0.002724996\right)
\end{aligned}
$$

Generalized Regression for N5 (MTTR)

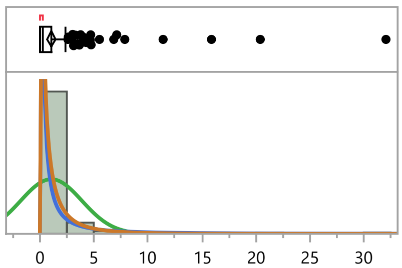
Standard Least Squares

Prediction Expression

$$+\left(2A7S1-6.007751938\right)\cdot\left(\left(2A7X3-11.968992248\right)\cdot 0.0008389346\right)$$

Distributions

Studentized Resid N5 (MTTR)^2



Compare Distributions

Distribution		AICc	AICc Weight	.2 .4 .6 .8	BIC	-2*LogLikelihood
Weibull		273.18713	1		280.24599	269.14007
Lognormal		313.75535	0		320.81421	309.70829
Normal		1272.875	0		1279.9339	1268.828

Quantiles

100.0%	maximum	32.049545747
99.5%		28.615524153
97.5%		6.9836027011
90.0%		2.2518473975
75.0%	quartile	1.0395277521
50.0%	median	0.3035075928
25.0%	quartile	0.062550515
10.0%		0.0069052291
2.5%		0.0002929408
0.5%		0.0000666399
0.0%	minimum	0.0000595176

Summary Statistics

Mean	1.0539848
Std Dev	2.8347915
Std Err Mean	0.1764864
Upper 95% Mean	1.4015284
Lower 95% Mean	0.7064411
N	258

Fitted Normal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Location	μ	1.0539848	0.1764864	0.7080778	1.3998918
Dispersion	σ	2.8347915	0.0743365	2.6927755	2.8559744

Measures	
-2*LogLikelihood	1268.828
AICc	1272.875
BIC	1279.9339

Distributions

Studentized Resid N5 (MTTR)^2

Fitted Lognormal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	μ	-1.691559	0.1490237	-1.98473	-1.398387
Shape	σ	2.3936751	0.1053757	2.2011041	2.616054

Measures	
-2*LogLikelihood	309.70829
AICc	313.75535
BIC	320.81421

Fitted Weibull Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	α	0.5440384	0.0679923	0.424533	0.694197
Shape	β	0.5246253	0.0249797	0.4766804	0.5745657

Measures	
-2*LogLikelihood	269.14007
AICc	273.18713
BIC	280.24599

3.4 F-16 Regression Models

Generalized Regression for N5 (MTTR)

Model Comparison

Show	Response Distribution	Estimation Method	Validation Method	Nonzero Parameters	AICc	BIC	R-Square
☑	Weibull	Maximum Likelihood	None	32	-78.55306	-10.00716	0.8804328
☑	Normal	Standard Least Squares	None	32	-68.62403	-0.078125	0.7719385

Weibull Maximum Likelihood

Model Summary

Response	N5 (MTTR)
Distribution	Weibull
Estimation Method	Maximum Likelihood
Validation Method	None
Location Model Link	Identity
Scale Model Link	Identity

Measure	
Number of rows	133
Sum of Frequencies	127
-LogLikelihood	-82.51057
Number of Parameters	32
BIC	-10.00716
AICc	-78.55306
Generalized RSquare	0.8804328

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	1.3051905	0.013565	9257.7782	<.0001*	1.2786035	1.3317774
2A0X1K	0.0055127	0.0038656	2.0337424	0.1538	-0.002064	0.0130892
2A3P3	0.0027379	0.0005894	21.579169	<.0001*	0.0015827	0.003893
2A3X3	-0.000867	0.0003197	7.3619031	0.0067*	-0.001494	-0.000241
2A3X4	-0.003571	0.0008442	17.895636	<.0001*	-0.005226	-0.001917
2A6S6	0.009036	0.0028559	10.010671	0.0016*	0.0034385	0.0146334
2A6X1	-0.004554	0.0011	17.140125	<.0001*	-0.00671	-0.002398
2A6X4	0.0021121	0.0013013	2.6344547	0.1046	-0.000438	0.0046626
2A6X5	0.0188694	0.0036862	26.203919	<.0001*	0.0116446	0.0260941
2A6X6	-0.009777	0.0011027	78.606637	<.0001*	-0.011938	-0.007616
2A7X1	-0.007592	0.0025626	8.7776194	0.0030*	-0.012615	-0.00257
2A7X3	-0.001485	0.0007792	3.6315902	0.0567	-0.003012	0.0000423
2W1L1	0.0007107	0.0003618	3.8600003	0.0495*	1.7091e-6	0.0014198
2W1S1	-0.010298	0.0016925	37.016738	<.0001*	-0.013615	-0.00698
2W1X1	0.0031231	0.0025659	1.4815238	0.2235	-0.001906	0.0081522
(2A3X4-9.68504)*(2A3X4-9.68504)	0.0010308	0.0001815	32.259943	<.0001*	0.0006751	0.0013865
(2A6S6-3.76378)*(2A6S6-3.76378)	-0.00647	0.0014146	20.915578	<.0001*	-0.009242	-0.003697
(2A3X3-25.4882)*(2A6X1-7.29921)	0.0001487	9.2235e-5	2.5980868	0.1070	-3.211e-5	0.0003294
(2A3X4-9.68504)*(2A6X1-7.29921)	-0.001423	0.0003014	22.279117	<.0001*	-0.002014	-0.000832
(2A6X1-7.29921)*(2A6X1-7.29921)	0.0013458	0.0003356	16.081799	<.0001*	0.0006881	0.0020036
(2A3X4-9.68504)*(2A6X4-6.18898)	0.0011309	0.0003337	11.483078	0.0007*	0.0004768	0.001785
(2A3X4-9.68504)*(2A6X6-7.31496)	-0.00064	0.0001836	12.160693	0.0005*	-0.001	-0.00028

Generalized Regression for N5 (MTTR)

Weibull Maximum Likelihood

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
(2A7X1-3.74803)*(2A7X1-3.74803)	0.0070826	0.0012693	31.136342	<.0001*	0.0045949	0.0095704
(2A0X1K-2.69291)*(2A7X3-9.74803)	-0.003907	0.0006914	31.937568	<.0001*	-0.005262	-0.002552
(2A6X5-2.70079)*(2A7X3-9.74803)	-0.003115	0.0007073	19.400581	<.0001*	-0.004501	-0.001729
(2A6X6-7.31496)*(2A7X3-9.74803)	0.0008208	0.0001808	20.606026	<.0001*	0.0004664	0.0011751
(2W1L1-21.937)*(2W1L1-21.937)	-4.573e-5	2.8213e-5	2.6266505	0.1051	-0.000101	9.572e-6
(2A7X3-9.74803)*(2W1S1-4.88976)	0.0015008	0.000302	24.692495	<.0001*	0.0009089	0.0020928
(2A3P3-13.3937)*(2W1X1-5.45669)	-0.001089	0.0003995	7.4376796	0.0064*	-0.001872	-0.000306
(2A3X4-9.68504)*(2W1X1-5.45669)	-0.00116	0.0005174	5.0307435	0.0249*	-0.002174	-0.000146
(2A6S6-3.76378)*(2W1X1-5.45669)	0.000376	0.0013035	0.083194	0.7730	-0.002179	0.0029307

Weibull Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	0.0315944	0.0021903	208.06656	<.0001*	0.0273014	0.0358874

Effect Tests

Source	Nparm	DF	Wald ChiSquare	Prob > ChiSquare
2A6X6	1	1	78.606637	<.0001*
2W1S1	1	1	37.016738	<.0001*
2A3X4*2A3X4	1	1	32.259943	<.0001*
2A0X1K*2A7X3	1	1	31.937568	<.0001*
2A7X1*2A7X1	1	1	31.136342	<.0001*
2A6X5	1	1	26.203919	<.0001*
2A7X3*2W1S1	1	1	24.692495	<.0001*
2A3X4*2A6X1	1	1	22.279117	<.0001*
2A3P3	1	1	21.579169	<.0001*
2A6S6*2A6S6	1	1	20.915578	<.0001*
2A6X6*2A7X3	1	1	20.606026	<.0001*
2A6X5*2A7X3	1	1	19.400581	<.0001*
2A3X4	1	1	17.895636	<.0001*
2A6X1	1	1	17.140125	<.0001*
2A6X1*2A6X1	1	1	16.081799	<.0001*
2A3X4*2A6X6	1	1	12.160693	0.0005*
2A3X4*2A6X4	1	1	11.483078	0.0007*
2A6S6	1	1	10.010671	0.0016*
2A7X1	1	1	8.7776194	0.0030*
2A3P3*2W1X1	1	1	7.4376796	0.0064*
2A3X3	1	1	7.3619031	0.0067*
2A3X4*2W1X1	1	1	5.0307435	0.0249*
2W1L1	1	1	3.8600003	0.0495*
2A7X3	1	1	3.6315902	0.0567
2A6X4	1	1	2.6344547	0.1046
2W1L1*2W1L1	1	1	2.6266505	0.1051
2A3X3*2A6X1	1	1	2.5980868	0.1070
2A0X1K	1	1	2.0337424	0.1538

Generalized Regression for N5 (MTTR)

Weibull Maximum Likelihood

Effect Tests

Source	Nparm	DF	Wald ChiSquare	Prob > ChiSquare
2W1X1	1	1	1.4815238	0.2235
2A6S6*2W1X1	1	1	0.083194	0.7730

Prediction Expression

$$
\mathrm{Exp}\left(\begin{array}{l}
1.3051904532 \\
+0.0055127462 \bullet 2A0X1K \\
+0.0027378542 \bullet 2A3P3 \\
+-0.000867479 \bullet 2A3X3 \\
+-0.003571324 \bullet 2A3X4 \\
+0.0090359571 \bullet 2A6S6 \\
+-0.004554228 \bullet 2A6X1 \\
+0.002112137 \bullet 2A6X4 \\
+0.0188693726 \bullet 2A6X5 \\
+-0.00977694 \bullet 2A6X6 \\
+-0.007592174 \bullet 2A7X1 \\
+-0.001484925 \bullet 2A7X3 \\
+0.0007107394 \bullet 2W1L1 \\
+-0.010297508 \bullet 2W1S1 \\
+0.0031231447 \bullet 2W1X1 \\
+\left(2A3X4-9.6850393701\right)\bullet\left(\left(2A3X4-9.6850393701\right)\bullet 0.0010308328\right) \\
+\left(2A6S6-3.7637795276\right)\bullet\left(\left(2A6S6-3.7637795276\right)\bullet -0.006469528\right) \\
+\left(2A3X3-25.488188976\right)\bullet\left(\left(2A6X1-7.2992125984\right)\bullet 0.00014867\right) \\
+\left(2A3X4-9.6850393701\right)\bullet\left(\left(2A6X1-7.2992125984\right)\bullet -0.001422863\right)
\end{array}\right.
$$

Generalized Regression for N5 (MTTR)

Weibull Maximum Likelihood

Prediction Expression

$$
\begin{aligned}
&+\left(2A6X1-7.2992125984\right)\cdot\left(\left(2A6X1-7.2992125984\right)\cdot 0.0013458269\right)\\
&+\left(2A3X4-9.6850393701\right)\cdot\left(\left(2A6X4-6.188976378\right)\cdot 0.0011309037\right)\\
&+\left(2A3X4-9.6850393701\right)\cdot\left(\left(2A6X6-7.3149606299\right)\cdot -0.000640319\right)\\
&+\left(2A7X1-3.7480314961\right)\cdot\left(\left(2A7X1-3.7480314961\right)\cdot 0.007082618\right)\\
&+\left(2A0X1K-2.6929133858\right)\cdot\left(\left(2A7X3-9.7480314961\right)\cdot -0.003907366\right)\\
&+\left(2A6X5-2.7007874016\right)\cdot\left(\left(2A7X3-9.7480314961\right)\cdot -0.003115168\right)\\
&+\left(2A6X6-7.3149606299\right)\cdot\left(\left(2A7X3-9.7480314961\right)\cdot 0.0008207662\right)\\
&+\left(2W1L1-21.937007874\right)\cdot\left(\left(2W1L1-21.937007874\right)\cdot -0.000045725\right)\\
&+\left(2A7X3-9.7480314961\right)\cdot\left(\left(2W1S1-4.8897637795\right)\cdot 0.0015008095\right)\\
&+\left(2A3P3-13.393700787\right)\cdot\left(\left(2W1X1-5.4566929134\right)\cdot -0.001089435\right)\\
&+\left(2A3X4-9.6850393701\right)\cdot\left(\left(2W1X1-5.4566929134\right)\cdot -0.001160437\right)\\
&+\left(2A6S6-3.7637795276\right)\cdot\left(\left(2W1X1-5.4566929134\right)\cdot 0.0003759631\right)\Bigg)
\end{aligned}
$$

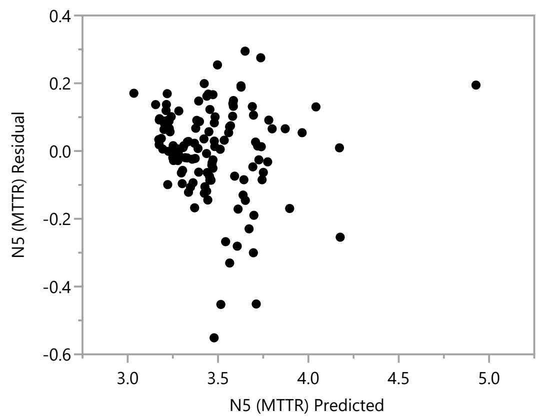
$$\cdot\,\text{Gamma}\left(1+0.0315943939\right)$$

Generalized Regression for N5 (MTTR)

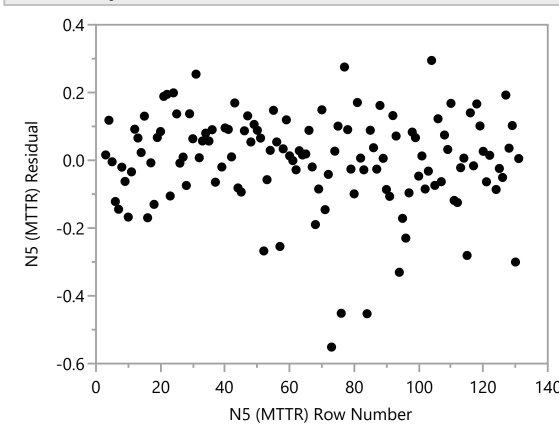
Weibull Maximum Likelihood

Diagnostic Bundle

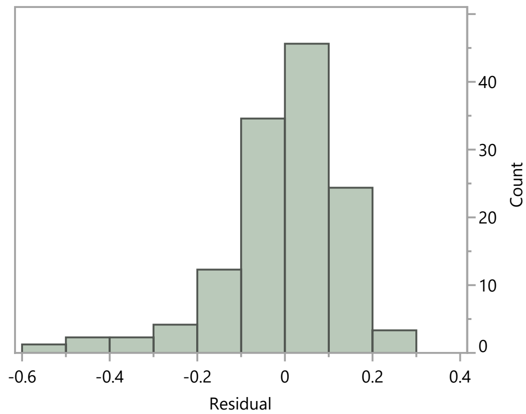
Residual by Predicted Plot



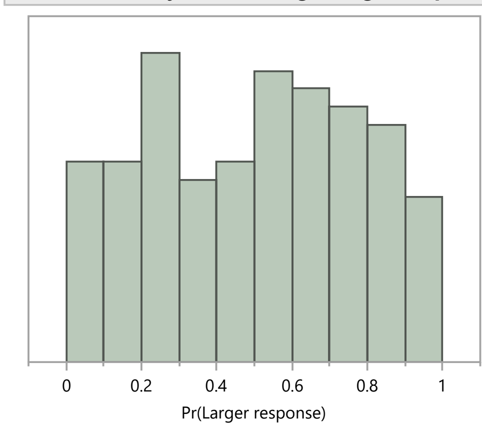
Residual by Row Plot



Histogram of Residuals



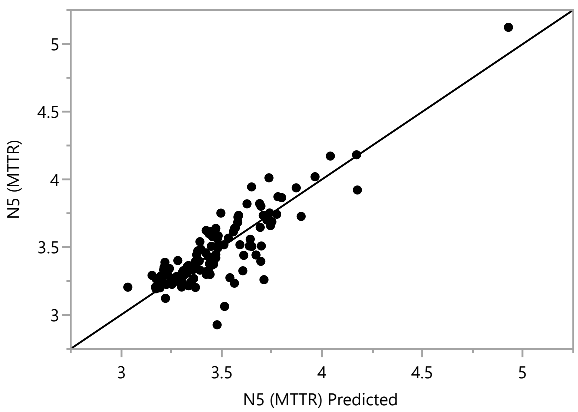
Fitted Probability of Observing a Larger Response



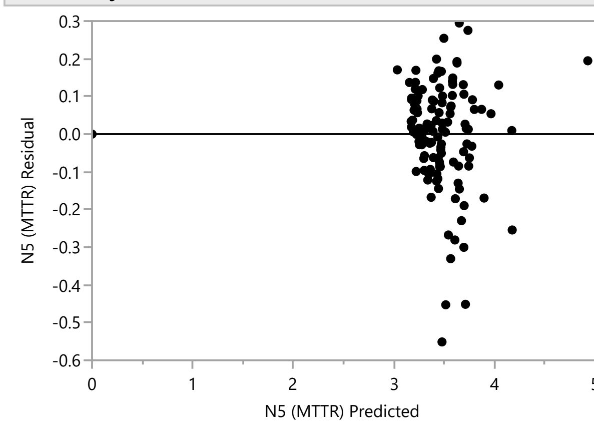
Generalized Regression for N5 (MTTR)

Weibull Maximum Likelihood

Actual by Predicted Plot



Residual by Predicted Plot



Standard Least Squares

Model Summary

Response	N5 (MTTR)
Distribution	Normal
Estimation Method	Standard Least Squares
Validation Method	None
Mean Model Link	Identity
Scale Model Link	Identity

Generalized Regression for N5 (MTTR)

Standard Least Squares

Model Summary

Measure	
Number of rows	133
Sum of Frequencies	127
-LogLikelihood	-77.54606
Number of Parameters	32
BIC	-0.078125
AICc	-68.62403
RSquare	0.7719385
RSquare Adj	0.7006692
RASE	0.1313963

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	3.4742046	0.0594984	3409.5709	<.0001*	3.3575898	3.5908194
2A0X1K	0.0192424	0.0187666	1.0513485	0.3052	-0.01754	0.0560243
2A3P3	0.0102996	0.0025967	15.732903	<.0001*	0.0052102	0.015389
2A3X3	-0.003807	0.0013483	7.9720366	0.0048*	-0.006449	-0.001164
2A3X4	-0.007539	0.0040152	3.5257518	0.0604	-0.015409	0.0003303
2A6S6	0.0298394	0.0121945	5.9875839	0.0144*	0.0059386	0.0537403
2A6X1	-0.017324	0.0049589	12.203993	0.0005*	-0.027043	-0.007604
2A6X4	0.0127323	0.0059339	4.6039036	0.0319*	0.001102	0.0243626
2A6X5	0.0815505	0.0181838	20.113334	<.0001*	0.0459109	0.1171901
2A6X6	-0.034503	0.0049744	48.107763	<.0001*	-0.044252	-0.024753
2A7X1	-0.015066	0.0112505	1.7932116	0.1805	-0.037116	0.0069849
2A7X3	-0.001922	0.0036409	0.2785483	0.5977	-0.009058	0.0052144
2W1L1	0.002809	0.0016857	2.7768594	0.0956	-0.000495	0.0061129
2W1S1	-0.036143	0.0073742	24.02195	<.0001*	-0.050596	-0.02169
2W1X1	0.0166281	0.010761	2.38768	0.1223	-0.004463	0.0377193
(2A3X4-9.68504)*(2A3X4-9.68504)	0.0035667	0.0008415	17.962995	<.0001*	0.0019173	0.0052161
(2A6S6-3.76378)*(2A6S6-3.76378)	-0.024133	0.0059513	16.443862	<.0001*	-0.035797	-0.012469
(2A3X3-25.4882)*(2A6X1-7.29921)	0.0005305	0.0003601	2.1703585	0.1407	-0.000175	0.0012363
(2A3X4-9.68504)*(2A6X1-7.29921)	-0.004991	0.001182	17.827229	<.0001*	-0.007308	-0.002674
(2A6X1-7.29921)*(2A6X1-7.29921)	0.0048208	0.0012985	13.782509	0.0002*	0.0022757	0.0073659
(2A3X4-9.68504)*(2A6X4-6.18898)	0.0042075	0.0015656	7.2224904	0.0072*	0.001139	0.007276
(2A3X4-9.68504)*(2A6X6-7.31496)	-0.002733	0.0008255	10.961102	0.0009*	-0.004351	-0.001115
(2A7X1-3.74803)*(2A7X1-3.74803)	0.019681	0.0054374	13.101359	0.0003*	0.009024	0.0303381
(2A0X1K-2.69291)*(2A7X3-9.74803)	-0.014221	0.0031451	20.44631	<.0001*	-0.020386	-0.008057
(2A6X5-2.70079)*(2A7X3-9.74803)	-0.011949	0.0032471	13.541522	0.0002*	-0.018313	-0.005585
(2A6X6-7.31496)*(2A7X3-9.74803)	0.0020649	0.0008194	6.351019	0.0117*	0.000459	0.0036709
(2W1L1-21.937)*(2W1L1-21.937)	-0.000294	0.0001345	4.7699066	0.0290*	-0.000557	-3.013e-5
(2A7X3-9.74803)*(2W1S1-4.88976)	0.0046427	0.0012712	13.338434	0.0003*	0.0021512	0.0071342
(2A3P3-13.3937)*(2W1X1-5.45669)	-0.004775	0.0017004	7.8855733	0.0050*	-0.008108	-0.001442
(2A3X4-9.68504)*(2W1X1-5.45669)	-0.005474	0.0023016	5.6568556	0.0174*	-0.009985	-0.000963
(2A6S6-3.76378)*(2W1X1-5.45669)	0.0057711	0.0055967	1.0632692	0.3025	-0.005198	0.0167404

Generalized Regression for N5 (MTTR)

Standard Least Squares

Parameter Estimates for Original Predictors

Normal Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	0.1511295	0.0119107	161	<.0001*	0.127785	0.174474

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
2A6X6	1	1	1.0987879	48.107763	<.0001*
2W1S1	1	1	0.5486646	24.02195	<.0001*
2A0X1K*2A7X3	1	1	0.4669965	20.44631	<.0001*
2A6X5	1	1	0.4593913	20.113334	<.0001*
2A3X4*2A3X4	1	1	0.4102773	17.962995	<.0001*
2A3X4*2A6X1	1	1	0.4071763	17.827229	<.0001*
2A6S6*2A6S6	1	1	0.3755801	16.443862	0.0001*
2A3P3	1	1	0.3593417	15.732903	0.0001*
2A6X1*2A6X1	1	1	0.3147944	13.782509	0.0003*
2A6X5*2A7X3	1	1	0.3092902	13.541522	0.0004*
2A7X3*2W1S1	1	1	0.3046517	13.338434	0.0004*
2A7X1*2A7X1	1	1	0.2992368	13.101359	0.0005*
2A6X1	1	1	0.2787409	12.203993	0.0007*
2A3X4*2A6X6	1	1	0.2503531	10.961102	0.0013*
2A3X3	1	1	0.1820824	7.9720366	0.0058*
2A3P3*2W1X1	1	1	0.1801076	7.8855733	0.0060*
2A3X4*2A6X4	1	1	0.1649627	7.2224904	0.0085*
2A6X6*2A7X3	1	1	0.1450581	6.351019	0.0134*
2A6S6	1	1	0.1367572	5.9875839	0.0162*
2A3X4*2W1X1	1	1	0.1292034	5.6568556	0.0194*
2W1L1*2W1L1	1	1	0.1089453	4.7699066	0.0314*
2A6X4	1	1	0.1051538	4.6039036	0.0344*
2A3X4	1	1	0.0805287	3.5257518	0.0635
2W1L1	1	1	0.0634238	2.7768594	0.0989
2W1X1	1	1	0.0545349	2.38768	0.1256
2A3X3*2A6X1	1	1	0.0495713	2.1703585	0.1440
2A7X1	1	1	0.0409572	1.7932116	0.1837
2A6S6*2W1X1	1	1	0.0242852	1.0632692	0.3051
2A0X1K	1	1	0.0240129	1.0513485	0.3078
2A7X3	1	1	0.0063621	0.2785483	0.5989

Generalized Regression for N5 (MTTR)

Standard Least Squares

Prediction Expression

$$
\begin{aligned}
&3.4742045898\\
&+ 0.0192424212 \cdot 2A0X1K\\
&+ 0.0102996318 \cdot 2A3P3\\
&+ -0.003806779 \cdot 2A3X3\\
&+ -0.007539322 \cdot 2A3X4\\
&+ 0.0298394347 \cdot 2A6S6\\
&+ -0.017323673 \cdot 2A6X1\\
&+ 0.0127322868 \cdot 2A6X4\\
&+ 0.0815505045 \cdot 2A6X5\\
&+ -0.034502587 \cdot 2A6X6\\
&+ -0.015065574 \cdot 2A7X1\\
&+ -0.001921572 \cdot 2A7X3\\
&+ 0.0028090335 \cdot 2W1L1\\
&+ -0.036142813 \cdot 2W1S1\\
&+ 0.0166280699 \cdot 2W1X1\\
&+ \left(2A3X4 - 9.6850393701\right) \cdot \left(\left(2A3X4 - 9.6850393701\right) \cdot 0.0035666767\right)\\
&+ \left(2A6S6 - 3.7637795276\right) \cdot \left(\left(2A6S6 - 3.7637795276\right) \cdot -0.024133065\right)\\
&+ \left(2A3X3 - 25.488188976\right) \cdot \left(\left(2A6X1 - 7.2992125984\right) \cdot 0.0005305021\right)\\
&+ \left(2A3X4 - 9.6850393701\right) \cdot \left(\left(2A6X1 - 7.2992125984\right) \cdot -0.004990884\right)\\
&+ \left(2A6X1 - 7.2992125984\right) \cdot \left(\left(2A6X1 - 7.2992125984\right) \cdot 0.0048207889\right)\\
&+ \left(2A3X4 - 9.6850393701\right) \cdot \left(\left(2A6X4 - 6.188976378\right) \cdot 0.0042074876\right)
\end{aligned}
$$

Generalized Regression for N5 (MTTR)

Standard Least Squares

Prediction Expression

$$+\left(2A3X4-9.6850393701\right)\cdot\left(\left(2A6X6-7.3149606299\right)\cdot -0.002732993\right)$$

$$+\left(2A7X1-3.7480314961\right)\cdot\left(\left(2A7X1-3.7480314961\right)\cdot 0.0196810043\right)$$

$$+\left(2A0X1K-2.6929133858\right)\cdot\left(\left(2A7X3-9.7480314961\right)\cdot -0.014221398\right)$$

$$+\left(2A6X5-2.7007874016\right)\cdot\left(\left(2A7X3-9.7480314961\right)\cdot -0.011948796\right)$$

$$+\left(2A6X6-7.3149606299\right)\cdot\left(\left(2A7X3-9.7480314961\right)\cdot 0.0020649359\right)$$

$$+\left(2W1L1-21.937007874\right)\cdot\left(\left(2W1L1-21.937007874\right)\cdot -0.000293727\right)$$

$$+\left(2A7X3-9.7480314961\right)\cdot\left(\left(2W1S1-4.8897637795\right)\cdot 0.0046426741\right)$$

$$+\left(2A3P3-13.393700787\right)\cdot\left(\left(2W1X1-5.4566929134\right)\cdot -0.004774881\right)$$

$$+\left(2A3X4-9.6850393701\right)\cdot\left(\left(2W1X1-5.4566929134\right)\cdot -0.005474217\right)$$

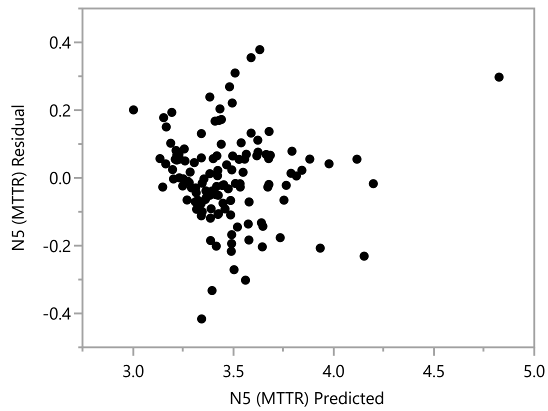
$$+\left(2A6S6-3.7637795276\right)\cdot\left(\left(2W1X1-5.4566929134\right)\cdot 0.005771055\right)$$

Generalized Regression for N5 (MTTR)

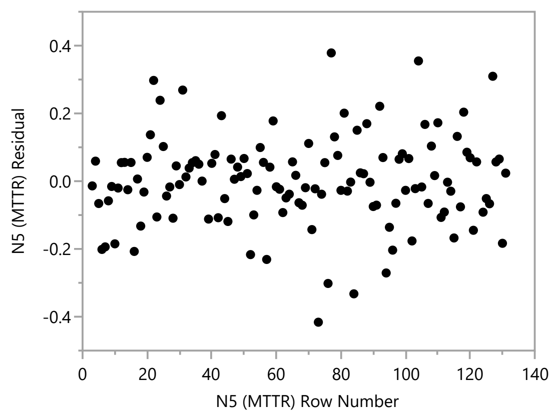
Standard Least Squares

Diagnostic Bundle

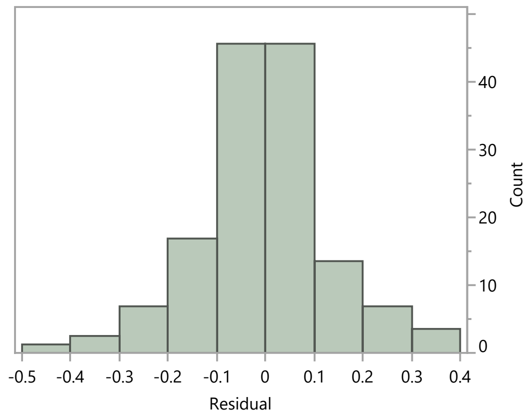
Residual by Predicted Plot



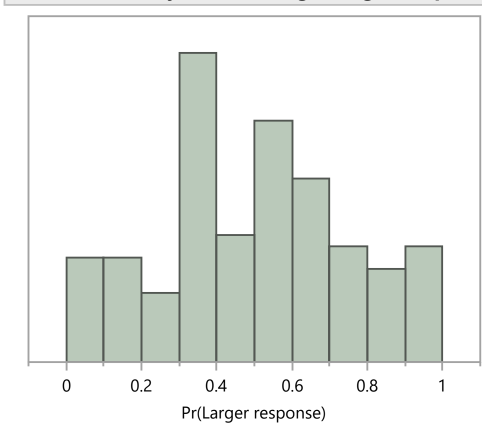
Residual by Row Plot



Histogram of Residuals



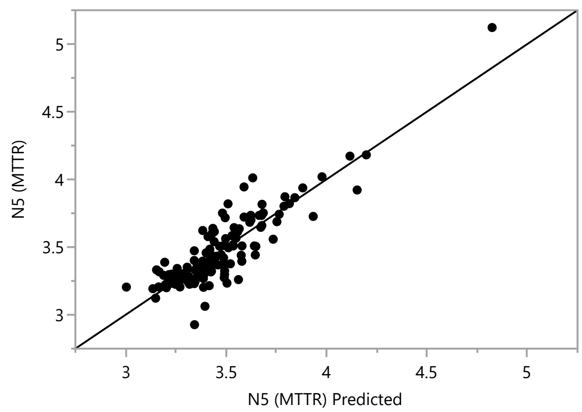
Fitted Probability of Observing a Larger Response



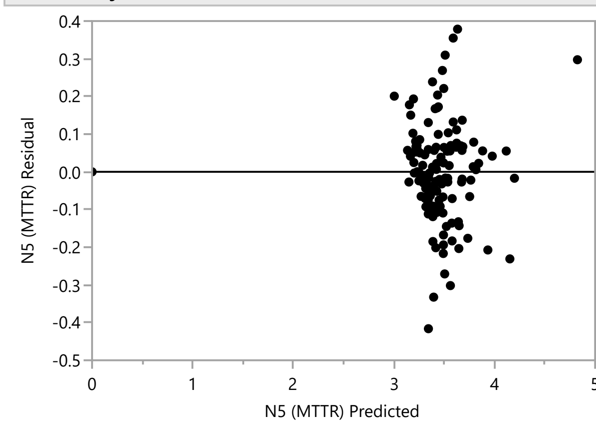
Generalized Regression for N5 (MTTR)

Standard Least Squares

Actual by Predicted Plot



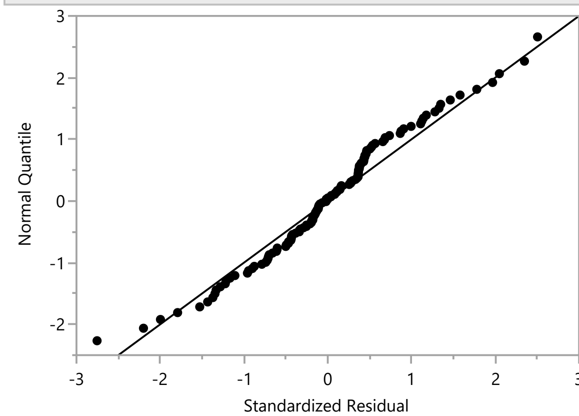
Residual by Predicted Plot



Generalized Regression for N5 (MTTR)

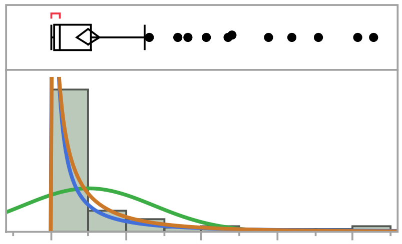
Standard Least Squares

Normal Quantile Plot



Distributions

Studentized Resid N5 (MTTR)^2



Compare Distributions

Distribution		AICc	AICc Weight	.2 .4 .6 .8	BIC	-2*LogLikelihood
Weibull		168.74236	1		174.33396	164.64558
Lognormal		194.04102	3.2e-6		199.63262	189.94424
Normal		502.45739	0		508.04899	498.36062

Quantiles

100.0%	maximum	8.544148337
99.5%		8.544148337
97.5%		7.9162712625
90.0%		2.5007159442
75.0%	quartile	1.064562522
50.0%	median	0.2425803691
25.0%	quartile	0.0793800755
10.0%		0.0149424778
2.5%		0.0004679594
0.5%		3.1238972e-6
0.0%	minimum	3.1238972e-6

Summary Statistics

Mean	1.0000121
Std Dev	1.7281443
Std Err Mean	0.153348
Upper 95% Mean	1.3034833
Lower 95% Mean	0.6965409
N	127

Fitted Normal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Location	μ	1.0000121	0.153348	0.6994555	1.3005686
Dispersion	σ	1.7281443	0.0829761	1.5729319	1.7544791

Measures	
-2*LogLikelihood	498.36062
AICc	502.45739
BIC	508.04899

Distributions

Studentized Resid N5 (MTTR)^2

Fitted Lognormal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	μ	-1.485732	0.2003904	-1.881479	-1.089985
Shape	σ	2.2582849	0.1416974	2.0066524	2.5672609

Measures	
-2*LogLikelihood	189.94424
AICc	194.04102
BIC	199.63262

Fitted Weibull Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	α	0.6175974	0.1012001	0.444948	0.8501265
Shape	β	0.5704718	0.0392438	0.4961045	0.6499157

Measures	
-2*LogLikelihood	164.64558
AICc	168.74236
BIC	174.33396

3.5 KC-46 Regression Models

Generalized Regression for N4

Model Comparison

Show	Response Distribution	Estimation Method	Validation Method	Nonzero Parameters	AICc	BIC	R-Square
☑	Weibull	Maximum Likelihood	None	15	43.576481	43.329265	0.9923416
☑	Normal	Standard Least Squares	None	15	56.6025	56.355284	0.9866255

Weibull Maximum Likelihood

Model Summary

Response	N4
Distribution	Weibull
Estimation Method	Maximum Likelihood
Validation Method	None
Location Model Link	Identity
Scale Model Link	Identity

Measure	
Number of rows	36
Sum of Frequencies	36
-LogLikelihood	-5.211759
Number of Parameters	15
BIC	43.329265
AICc	43.576481
Generalized RSquare	0.9923416

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	3.5679133	0.0327657	11857.377	<.0001*	3.5036936	3.632133
2A5X1	-0.087712	0.0015479	3211.0368	<.0001*	-0.090745	-0.084678
2A5X3A	-0.010683	0.0038249	7.8005199	0.0052*	-0.018179	-0.003186
2A5X3B	0.0028125	0.0035783	0.6177816	0.4319	-0.004201	0.0098258
2A5X3C	0.0305616	0.0036834	68.84105	<.0001*	0.0233422	0.037781
2A6X5	-0.022239	0.0031206	50.784942	<.0001*	-0.028355	-0.016122
2A6X6	-0.008814	0.002706	10.60923	0.0011*	-0.014118	-0.00351
2A7X1	0.0120135	0.0036079	11.087504	0.0009*	0.0049422	0.0190848
(2A5X1-7.47222)*(2A5X1-7.47222)	0.0318361	0.002627	146.86016	<.0001*	0.0266871	0.036985
(2A5X1-7.47222)*(2A5X3B-3.5)	0.0224295	0.004023	31.084243	<.0001*	0.0145446	0.0303144
(2A5X3A-2.5)*(2A5X3C-3.5)	0.0401465	0.008121	24.438512	<.0001*	0.0242296	0.0560634
(2A5X3B-3.5)*(2A5X3C-3.5)	0.0443872	0.0075481	34.581682	<.0001*	0.0295933	0.0591811
(2A5X3A-2.5)*(2A6X5-3.5)	-0.029568	0.0075347	15.399533	<.0001*	-0.044335	-0.0148
(2A6X5-3.5)*(2A6X6-5)	0.0146524	0.0052028	7.9311568	0.0049*	0.004455	0.0248498

Weibull Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	0.0087558	0.0012681	47.673658	<.0001*	0.0062704	0.0112413

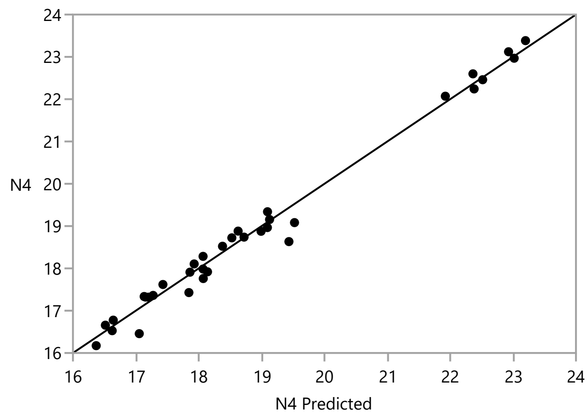
Generalized Regression for N4

Weibull Maximum Likelihood

Effect Tests

Source	Nparm	DF	Wald ChiSquare	Prob > ChiSquare
2A5X1	1	1	3211.0368	<.0001*
2A5X1*2A5X1	1	1	146.86016	<.0001*
2A5X3C	1	1	68.84105	<.0001*
2A6X5	1	1	50.784942	<.0001*
2A5X3B*2A5X3C	1	1	34.581682	<.0001*
2A5X1*2A5X3B	1	1	31.084243	<.0001*
2A5X3A*2A5X3C	1	1	24.438512	<.0001*
2A5X3A*2A6X5	1	1	15.399533	<.0001*
2A7X1	1	1	11.087504	0.0009*
2A6X6	1	1	10.60923	0.0011*
2A6X5*2A6X6	1	1	7.9311568	0.0049*
2A5X3A	1	1	7.8005199	0.0052*
2A5X3B	1	1	0.6177816	0.4319

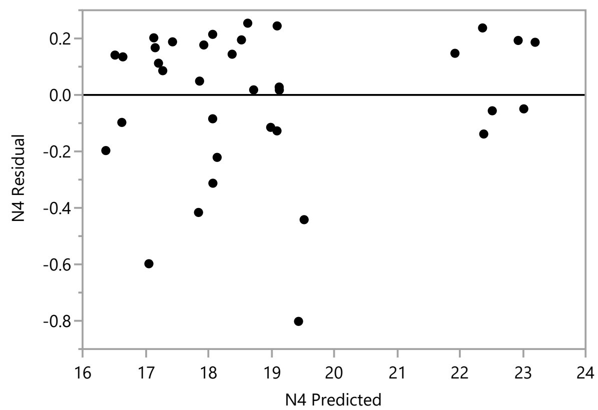
Actual by Predicted Plot



Generalized Regression for N4

Weibull Maximum Likelihood

Residual by Predicted Plot



Generalized Regression for N4

Weibull Maximum Likelihood

Prediction Expression

$$\mathrm{Exp}\left(\begin{array}{l}3.5679133073\\ +\,\text{-}0.08771156 \cdot 2A5X1\\ +\,\text{-}0.010682587 \cdot 2A5X3A\\ +\,0.0028124849 \cdot 2A5X3B\\ +\,0.030561618 \cdot 2A5X3C\\ +\,\text{-}0.022238588 \cdot 2A6X5\\ +\,\text{-}0.008813989 \cdot 2A6X6\\ +\,0.0120134593 \cdot 2A7X1\\ +\left(2A5X1 - 7.4722222222\right)\cdot\left(\left(2A5X1 - 7.4722222222\right)\cdot 0.0318360587\right)\\ +\left(2A5X1 - 7.4722222222\right)\cdot\left(\left(2A5X3B - 3.5\right)\cdot 0.0224294971\right)\\ +\left(2A5X3A - 2.5\right)\cdot\left(\left(2A5X3C - 3.5\right)\cdot 0.0401464976\right)\\ +\left(2A5X3B - 3.5\right)\cdot\left(\left(2A5X3C - 3.5\right)\cdot 0.0443872209\right)\\ +\left(2A5X3A - 2.5\right)\cdot\left(\left(2A6X5 - 3.5\right)\cdot \text{-}0.029567709\right)\\ +\left(2A6X5 - 3.5\right)\cdot\left(\left(2A6X6 - 5\right)\cdot 0.0146524195\right)\end{array}\right)$$

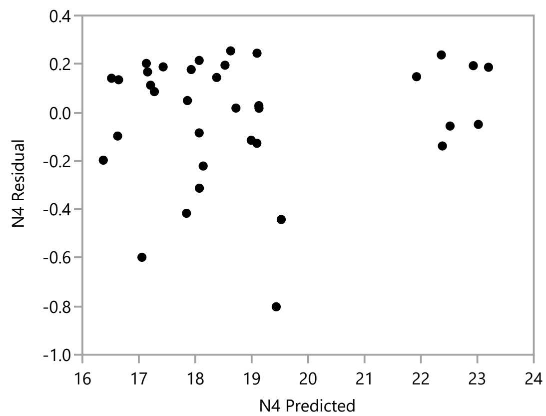
$$\cdot\,\mathrm{Gamma}\left(1 + 0.008755835\hat{8}\right)$$

Generalized Regression for N4

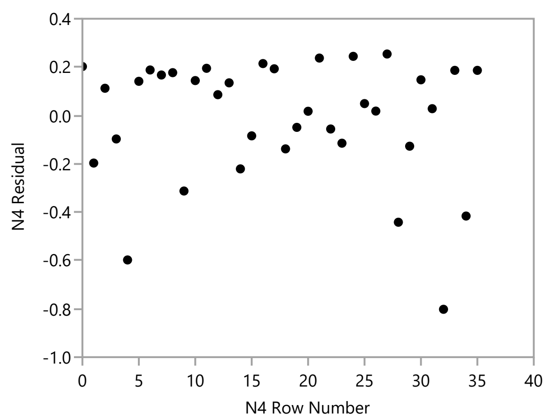
Weibull Maximum Likelihood

Diagnostic Bundle

Residual by Predicted Plot



Residual by Row Plot

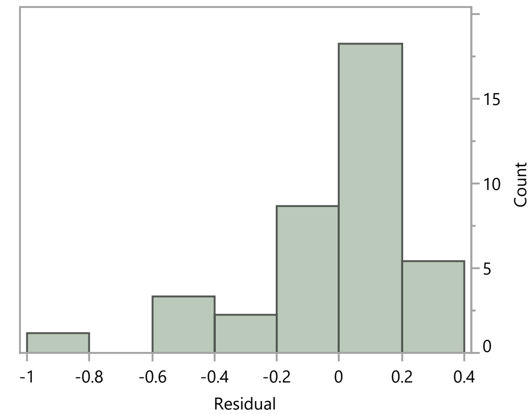


Standard Least Squares

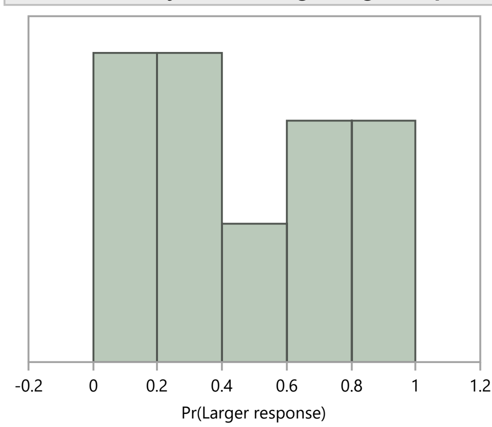
Model Summary

Response	N4
Distribution	Normal
Estimation Method	Standard Least Squares
Validation Method	None
Mean Model Link	Identity

Histogram of Residuals



Fitted Probability of Observing a Larger Response



Generalized Regression for N4

Standard Least Squares

Model Summary

Scale Model Link	Identity
Measure	
Number of rows	36
Sum of Frequencies	36
-LogLikelihood	1.3012502
Number of Parameters	15
BIC	56.355284
AICc	56.6025
RSquare	0.9866255
RSquare Adj	0.9787224
RASE	0.250877

Parameter Estimates for Original Predictors

Term	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Intercept	31.021561	0.7826211	1571.1737	<.0001*	29.487651	32.55547
2A5X1	-1.755318	0.0549082	1021.9685	<.0001*	-1.862936	-1.6477
2A5X3A	-0.125858	0.1126426	1.2484045	0.2639	-0.346633	0.0949176
2A5X3B	0.1193624	0.1099164	1.1792602	0.2775	-0.09607	0.3347946
2A5X3C	0.6153457	0.1100239	31.279829	<.0001*	0.3997028	0.8309885
2A6X5	-0.427638	0.1131047	14.295246	0.0002*	-0.649319	-0.205957
2A6X6	-0.190277	0.078671	5.8497997	0.0156*	-0.344469	-0.036084
2A7X1	0.1994477	0.1142541	3.0472949	0.0809	-0.024486	0.4233816
(2A5X1-7.47222)*(2A5X1-7.47222)	0.7643412	0.0665909	131.74821	<.0001*	0.6338254	0.894857
(2A5X1-7.47222)*(2A5X3B-3.5)	0.4808993	0.1151554	17.43973	<.0001*	0.2551989	0.7065997
(2A5X3A-2.5)*(2A5X3C-3.5)	0.5304331	0.2368535	5.0153552	0.0251*	0.0662088	0.9946573
(2A5X3B-3.5)*(2A5X3C-3.5)	0.5960488	0.240749	6.1296368	0.0133*	0.1241895	1.0679081
(2A5X3A-2.5)*(2A6X5-3.5)	-0.623873	0.2238691	7.7661308	0.0053*	-1.062649	-0.185098
(2A6X5-3.5)*(2A6X6-5)	0.3082449	0.1581104	3.8007634	0.0512	-0.001646	0.6181356

Normal Distribution Parameters	Estimate	Std Error	Wald ChiSquare	Prob > ChiSquare	Lower 95%	Upper 95%
Scale	0.3209229	0.0585922	30	<.0001*	0.2060842	0.4357615

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
2A5X1	1	1	105.25406	1021.9685	<.0001*
2A5X1*2A5X1	1	1	13.568944	131.74821	<.0001*
2A5X3C	1	1	3.2215563	31.279829	<.0001*
2A5X1*2A5X3B	1	1	1.7961438	17.43973	0.0004*
2A6X5	1	1	1.4722887	14.295246	0.0010*
2A5X3A*2A6X5	1	1	0.7998454	7.7661308	0.0108*
2A5X3B*2A5X3C	1	1	0.6313004	6.1296368	0.0215*
2A6X6	1	1	0.6024796	5.8497997	0.0243*
2A5X3A*2A5X3C	1	1	0.5165389	5.0153552	0.0356*
2A6X5*2A6X6	1	1	0.3914463	3.8007634	0.0641

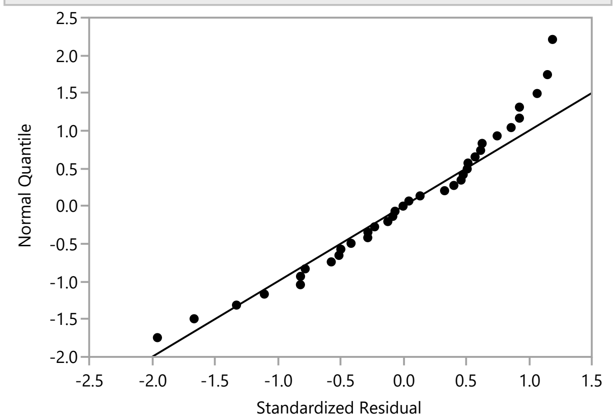
Generalized Regression for N4

Standard Least Squares

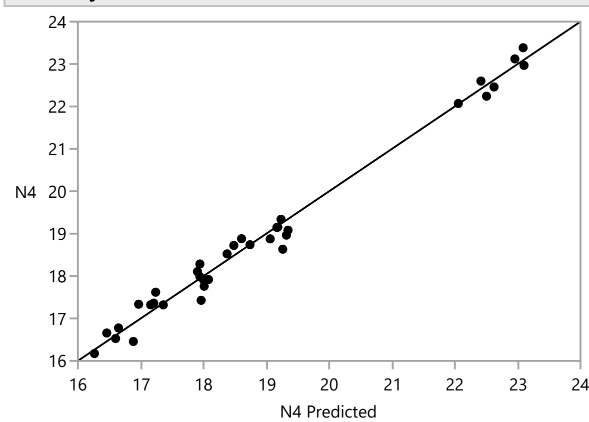
Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
2A7X1	1	1	0.3138454	3.0472949	0.0948
2A5X3A	1	1	0.128575	1.2484045	0.2759
2A5X3B	1	1	0.1214538	1.1792602	0.2893

Normal Quantile Plot



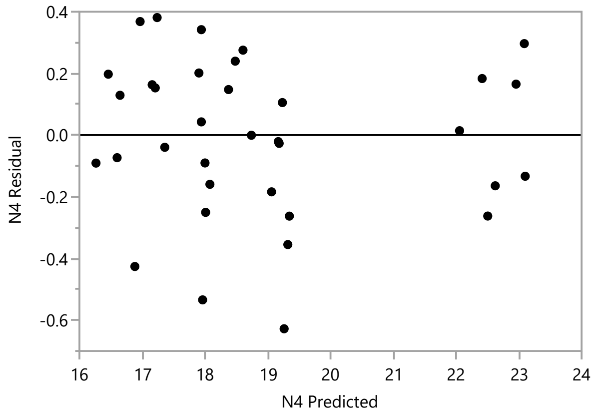
Actual by Predicted Plot



Generalized Regression for N4

Standard Least Squares

Residual by Predicted Plot



Generalized Regression for N4

Standard Least Squares

Prediction Expression

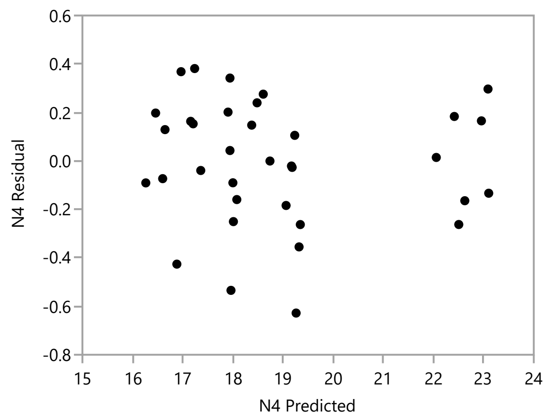
$$
\begin{aligned}
&31.021560513\\
&+ -1.755318361 \cdot 2A5X1\\
&+ -0.125857833 \cdot 2A5X3A\\
&+ 0.1193623689 \cdot 2A5X3B\\
&+ 0.6153456821 \cdot 2A5X3C\\
&+ -0.427638097 \cdot 2A6X5\\
&+ -0.190276527 \cdot 2A6X6\\
&+ 0.199447686 \cdot 2A7X1\\
&+\left(2A5X1 - 7.4722222222\right)\cdot\left(\left(2A5X1 - 7.4722222222\right)\cdot 0.7643411995\right)\\
&+\left(2A5X1 - 7.4722222222\right)\cdot\left(\left(2A5X3B - 3.5\right)\cdot 0.4808992749\right)\\
&+\left(2A5X3A - 2.5\right)\cdot\left(\left(2A5X3C - 3.5\right)\cdot 0.5304330723\right)\\
&+\left(2A5X3B - 3.5\right)\cdot\left(\left(2A5X3C - 3.5\right)\cdot 0.5960487803\right)\\
&+\left(2A5X3A - 2.5\right)\cdot\left(\left(2A6X5 - 3.5\right)\cdot -0.623873359\right)\\
&+\left(2A6X5 - 3.5\right)\cdot\left(\left(2A6X6 - 5\right)\cdot 0.308244898\right)
\end{aligned}
$$

Generalized Regression for N4

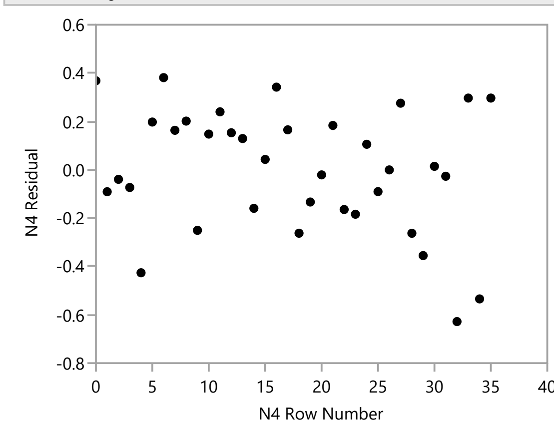
Standard Least Squares

Diagnostic Bundle

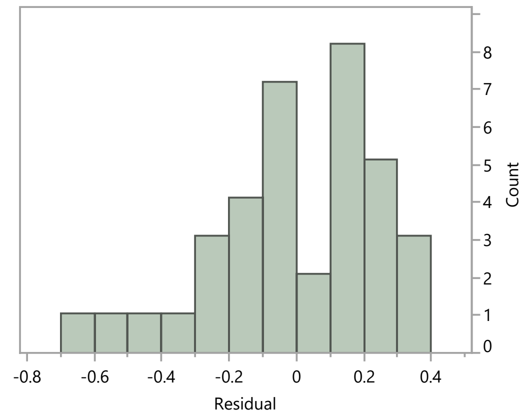
Residual by Predicted Plot



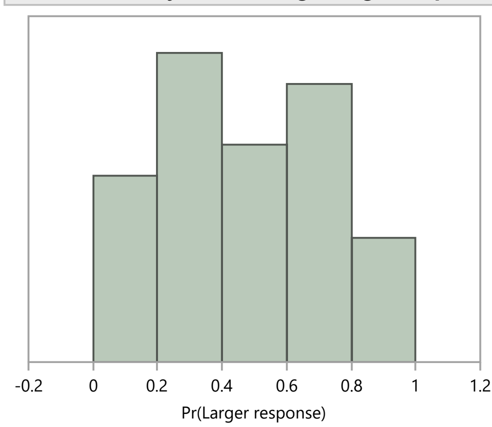
Residual by Row Plot



Histogram of Residuals

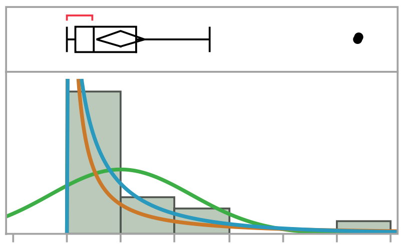


Fitted Probability of Observing a Larger Response



Distributions

Studentized Resid N4^2



Compare Distributions

Distribution		AICc	AICc Weight	.2 .4 .6 .8	BIC	-2*LogLikelihood
Weibull		64.012325	1		66.815727	59.648689
Lognormal		84.8308	3e-5		87.634201	80.467164
Normal		124.9474	0		127.7508	120.58376

Quantiles

100.0%	maximum	5.4055038209
99.5%		5.4055038209
97.5%		5.4055038209
90.0%		2.59094905
75.0%	quartile	1.2861934925
50.0%	median	0.4986273116
25.0%	quartile	0.150669752
10.0%		0.0092633108
2.5%		4.2262715e-6
0.5%		4.2262715e-6
0.0%	minimum	4.2262715e-6

Summary Statistics

Mean	0.9971596
Std Dev	1.309604
Std Err Mean	0.2182673
Upper 95% Mean	1.4402659
Lower 95% Mean	0.5540534
N	36

Fitted Normal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Location	μ	0.9971596	0.2182673	0.5693635	1.4249558
Dispersion	σ	1.309604	0.1377671	1.0656037	1.3813736

Measures	
-2*LogLikelihood	120.58376
AICc	124.9474
BIC	127.7508

Distributions

Studentized Resid N4^2

Fitted Lognormal Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	μ	-1.241568	0.4267614	-2.100823	-0.382314
Shape	σ	2.5605685	0.3017659	2.0662642	3.2885724

Measures	
-2*LogLikelihood	80.467164
AICc	84.8308
BIC	87.634201

Fitted Weibull Distribution

Parameter		Estimate	Std Error	Lower 95%	Upper 95%
Scale	α	0.7740059	0.2060631	0.4467292	1.3144848
Shape	β	0.6522998	0.0890909	0.4899631	0.8388222

Measures	
-2*LogLikelihood	59.648689
AICc	64.012325
BIC	66.815727

Appendix D. Plots of Model Output

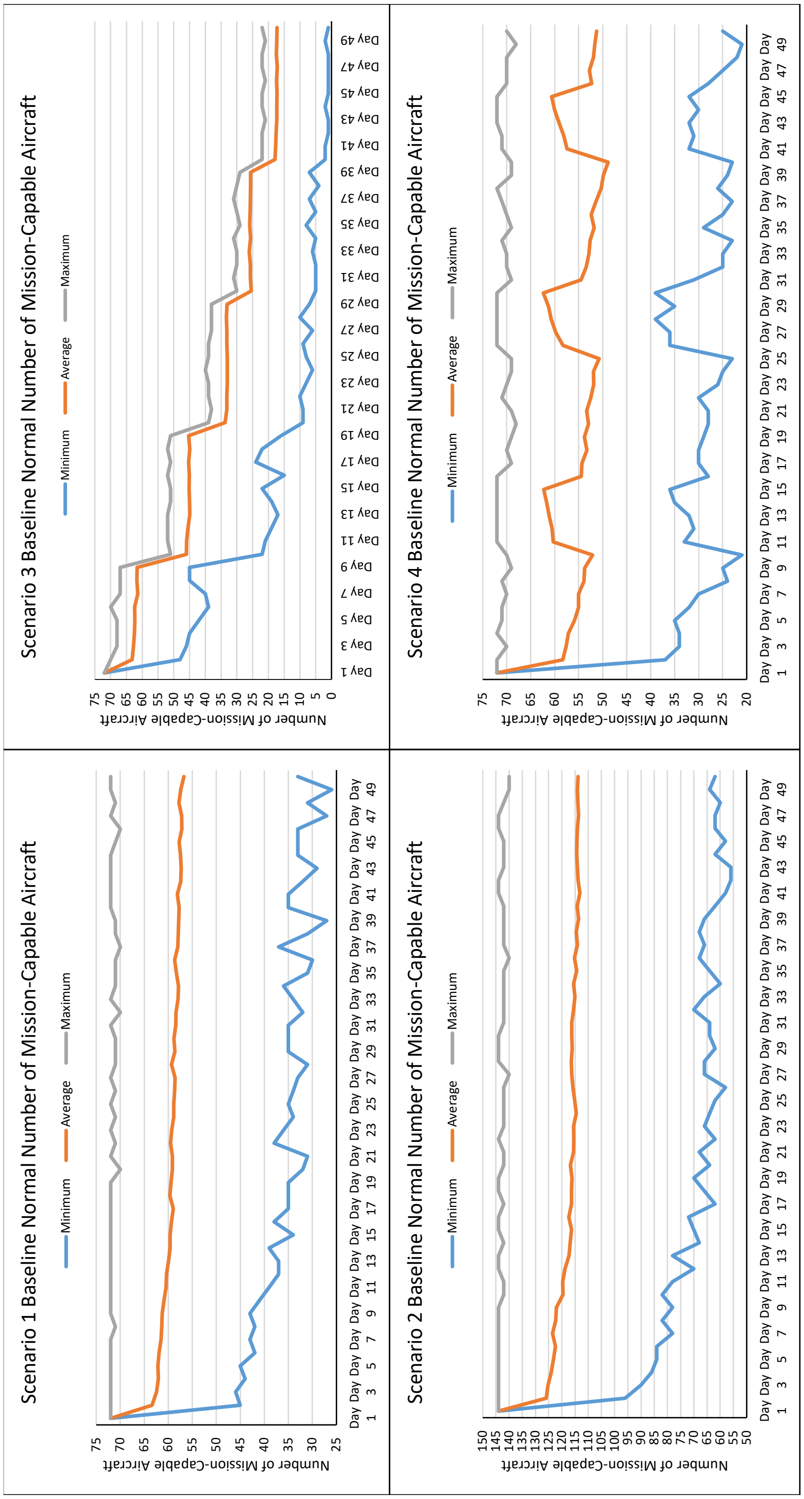


Figure 26. Scenarios 1 – 4 Baseline Normal Number of Mission-Capable Aircraft

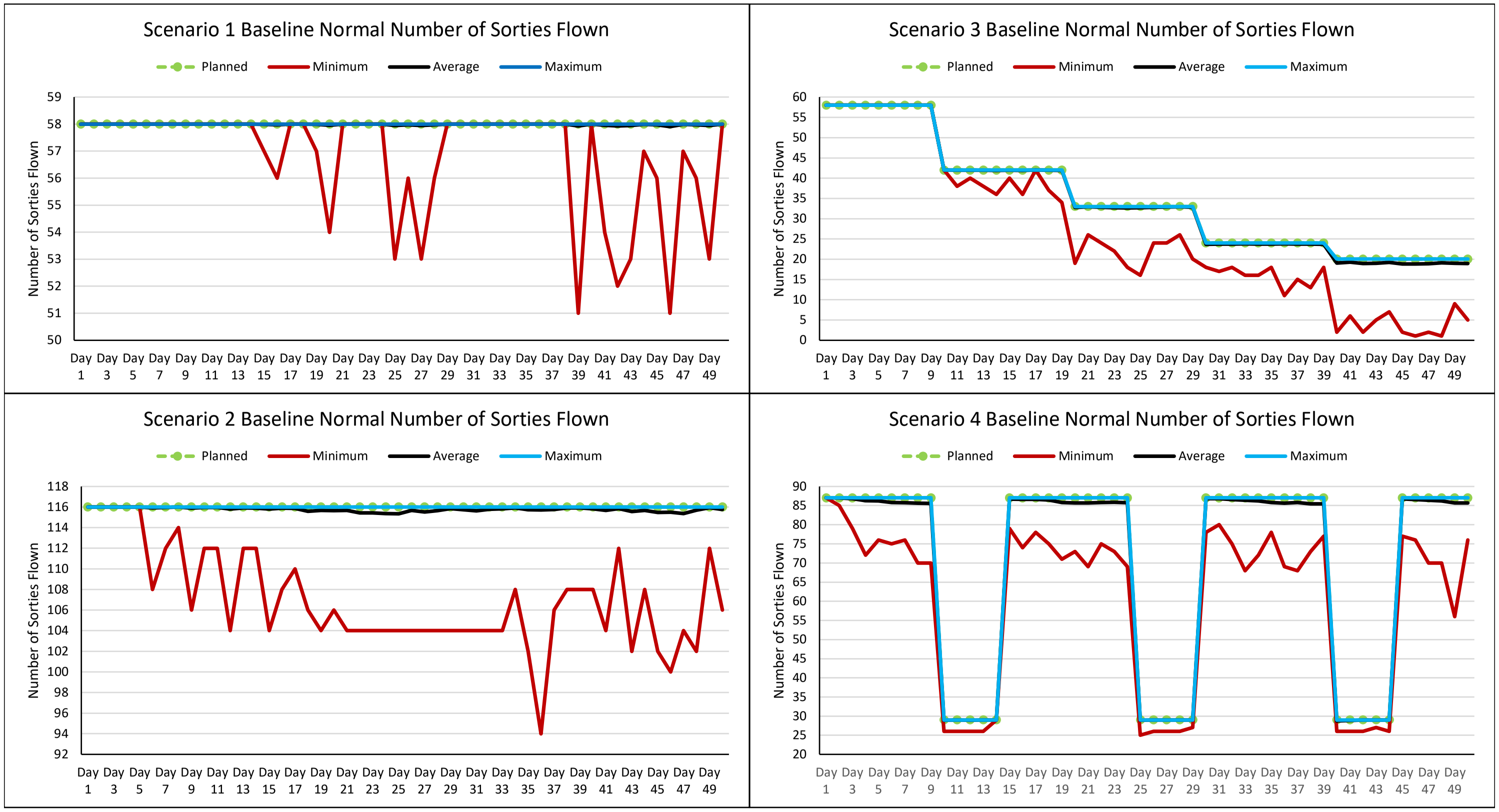


Figure 27. Scenarios 1 – 4 Baseline Normal Number of Sorties Flown

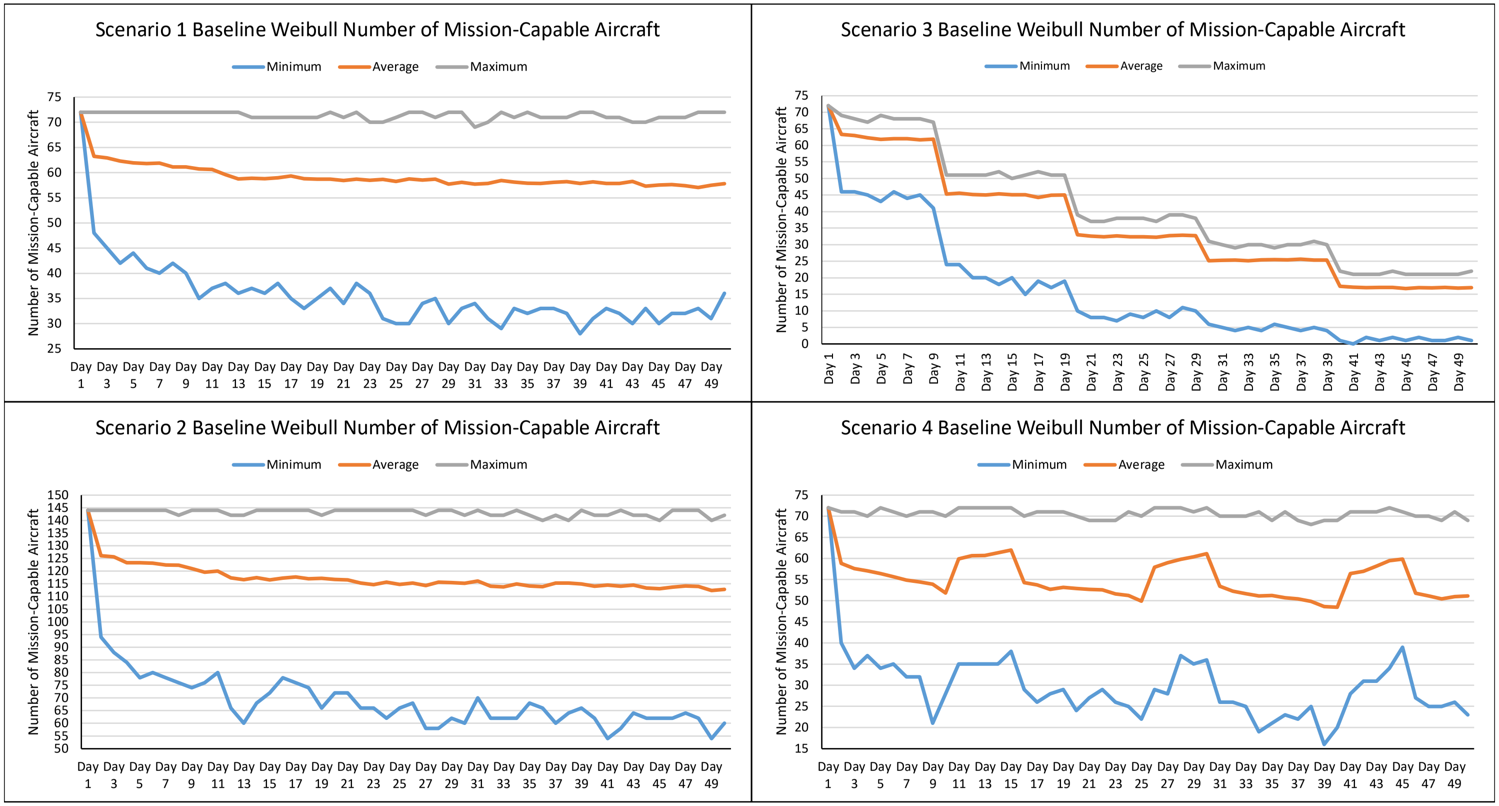


Figure 28. Scenarios 1 – 4 Baseline Weibull Number of Mission-Capable Aircraft

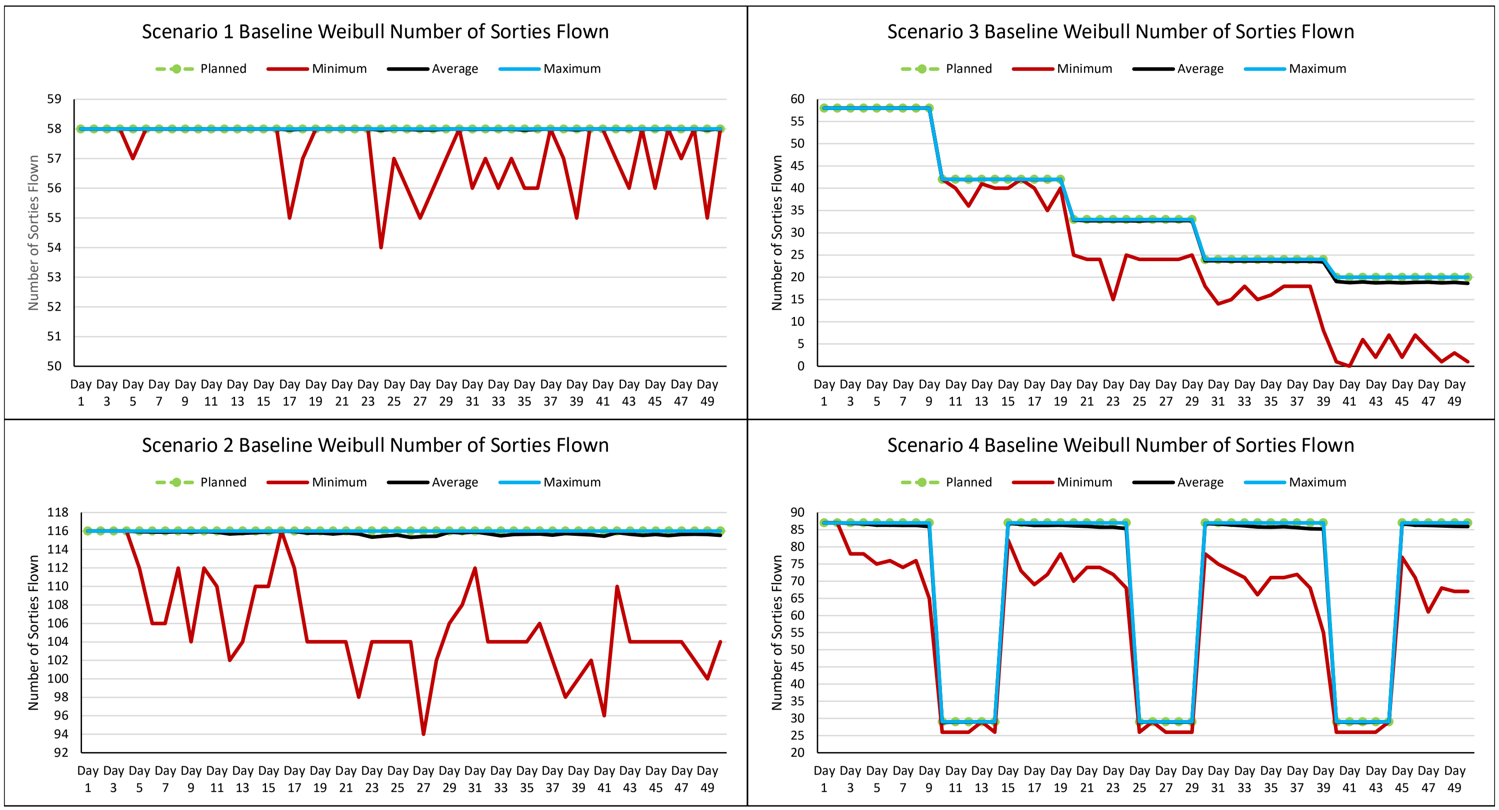


Figure 29. Scenarios 1 – 4 Baseline Weibull Number of Sorties Flown

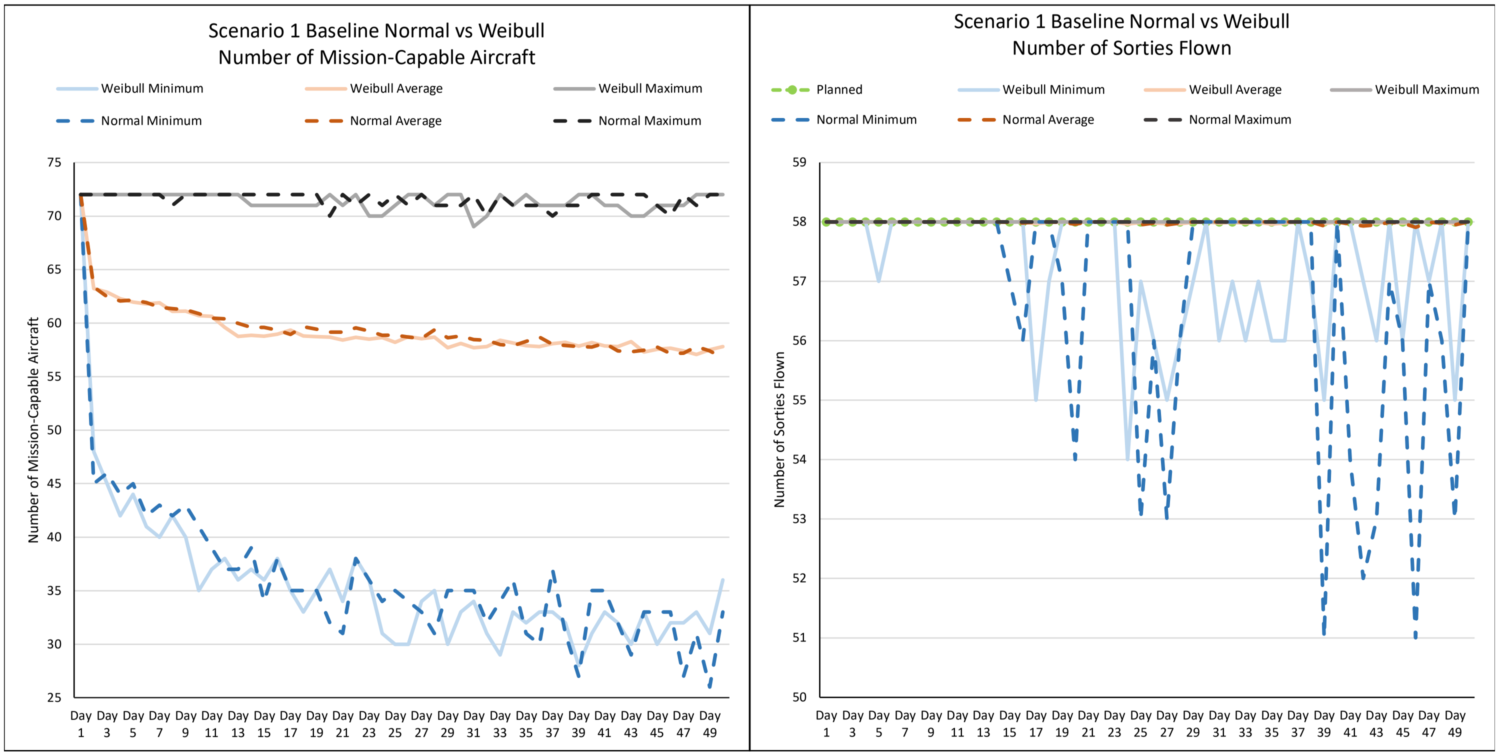


Figure 30. Scenario 1 Baseline Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

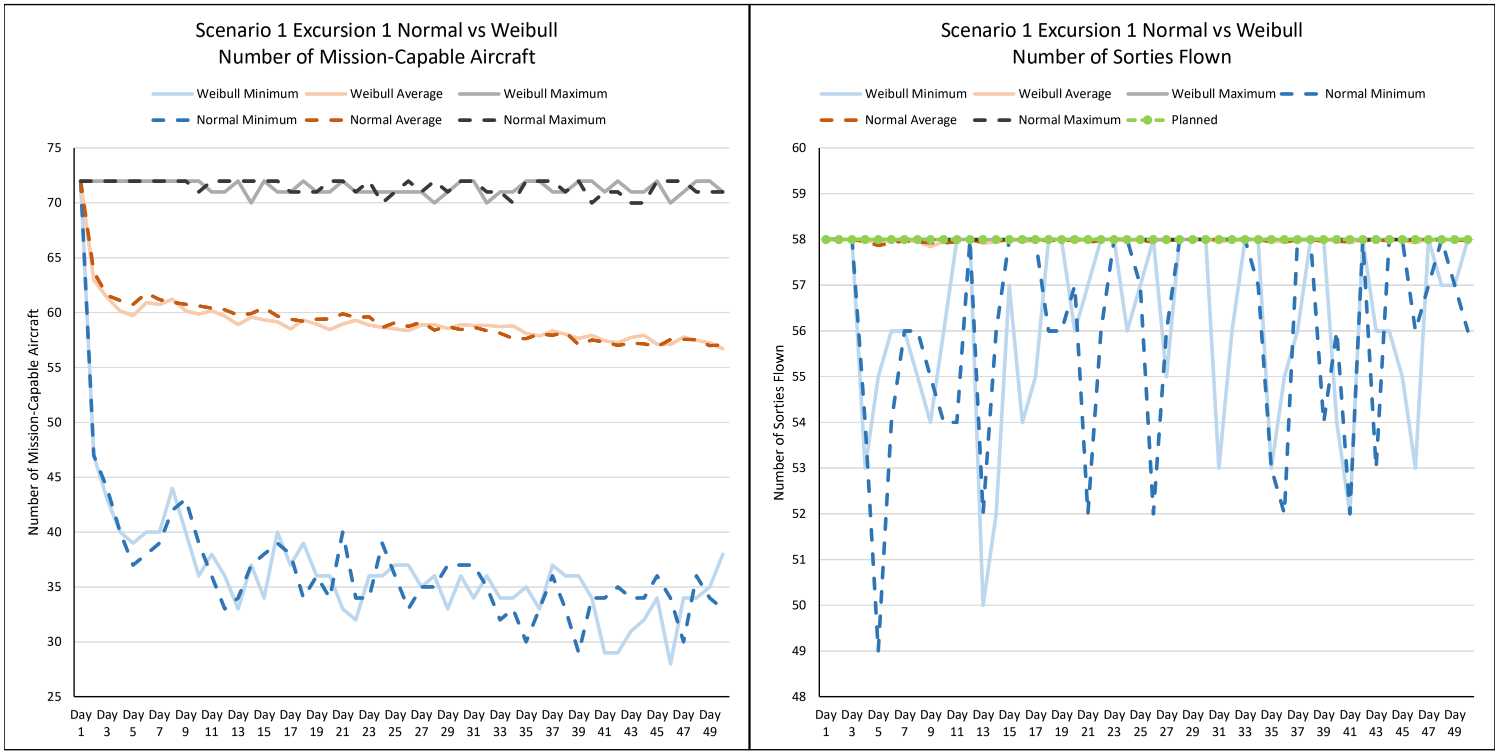


Figure 31. Scenario 1 Excursion 1 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

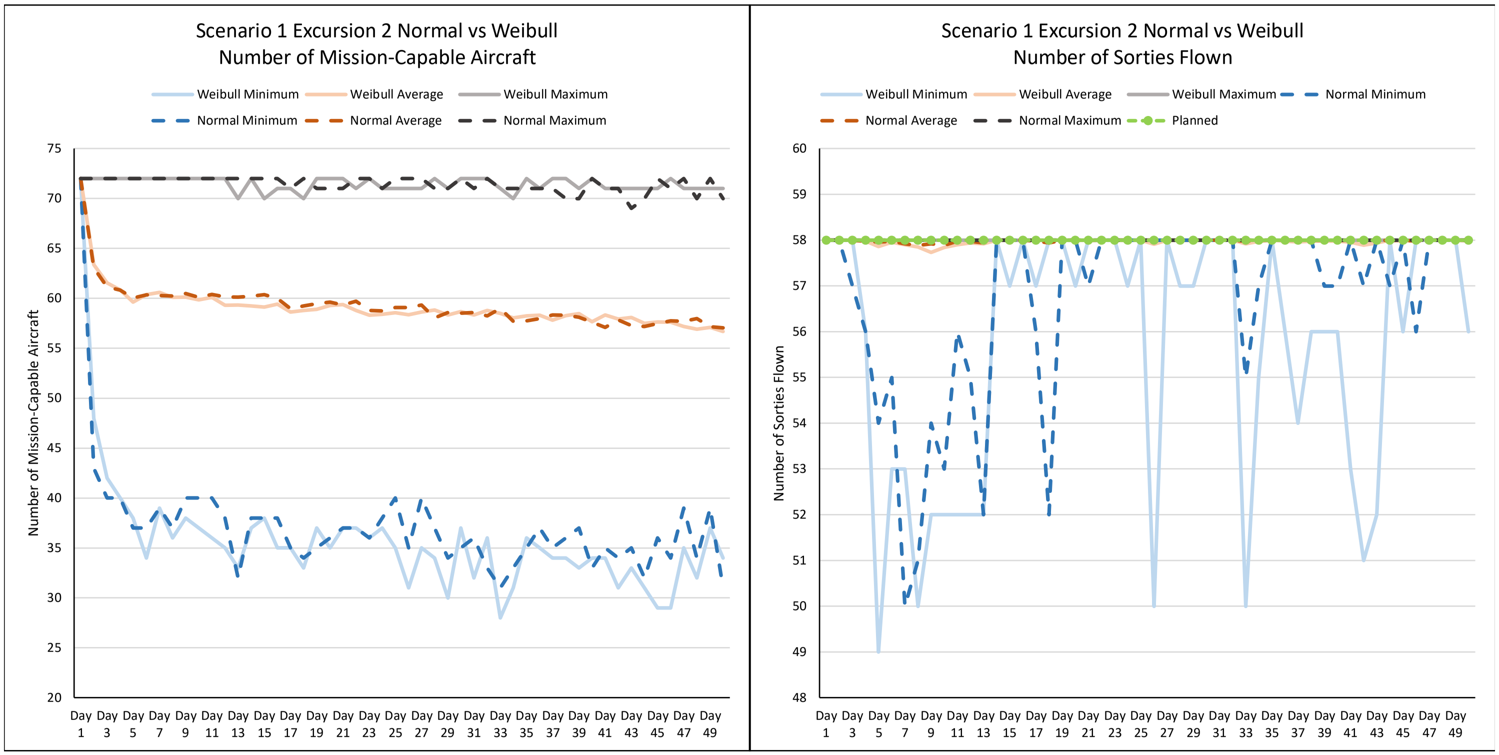


Figure 32. Scenario 1 Excursion 2 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

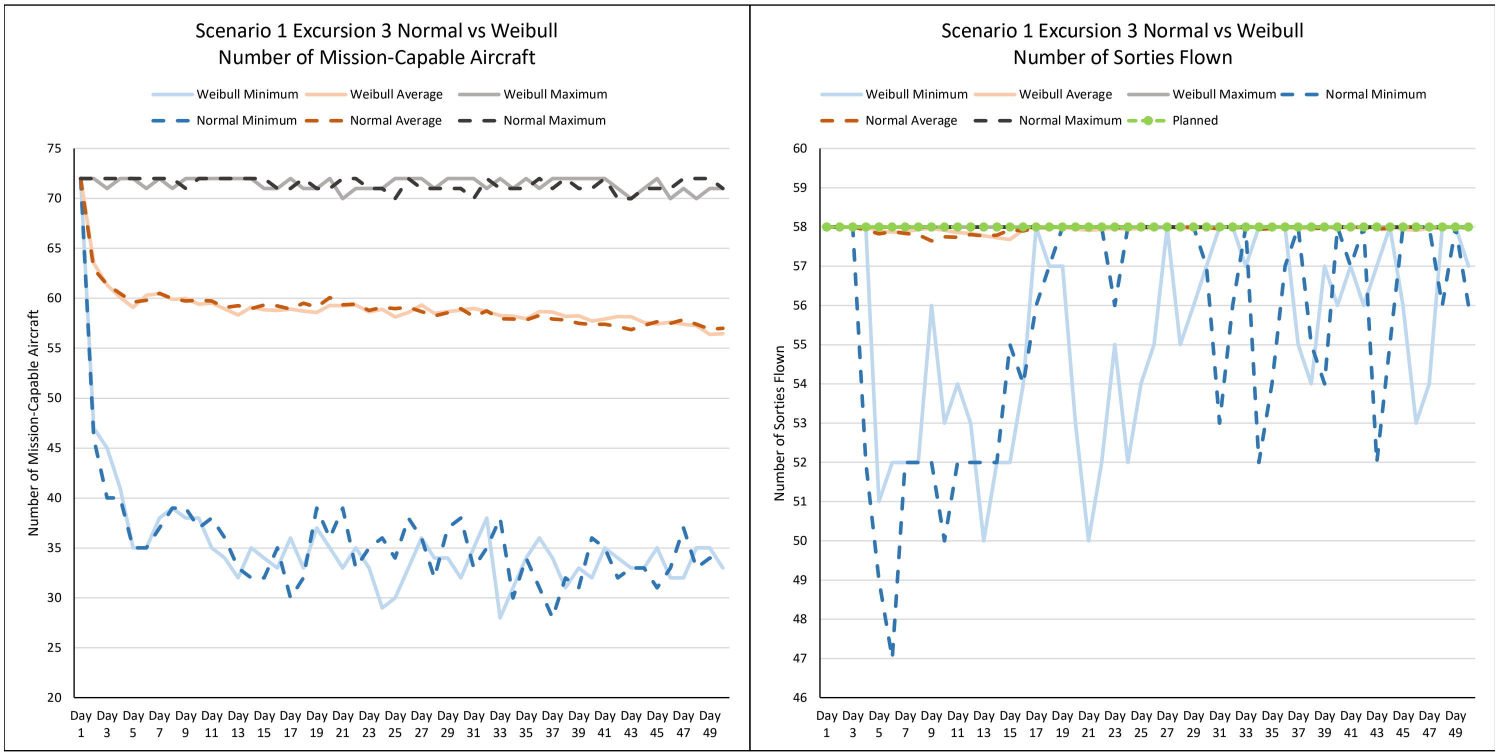


Figure 33. Scenario 1 Excursion 3 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

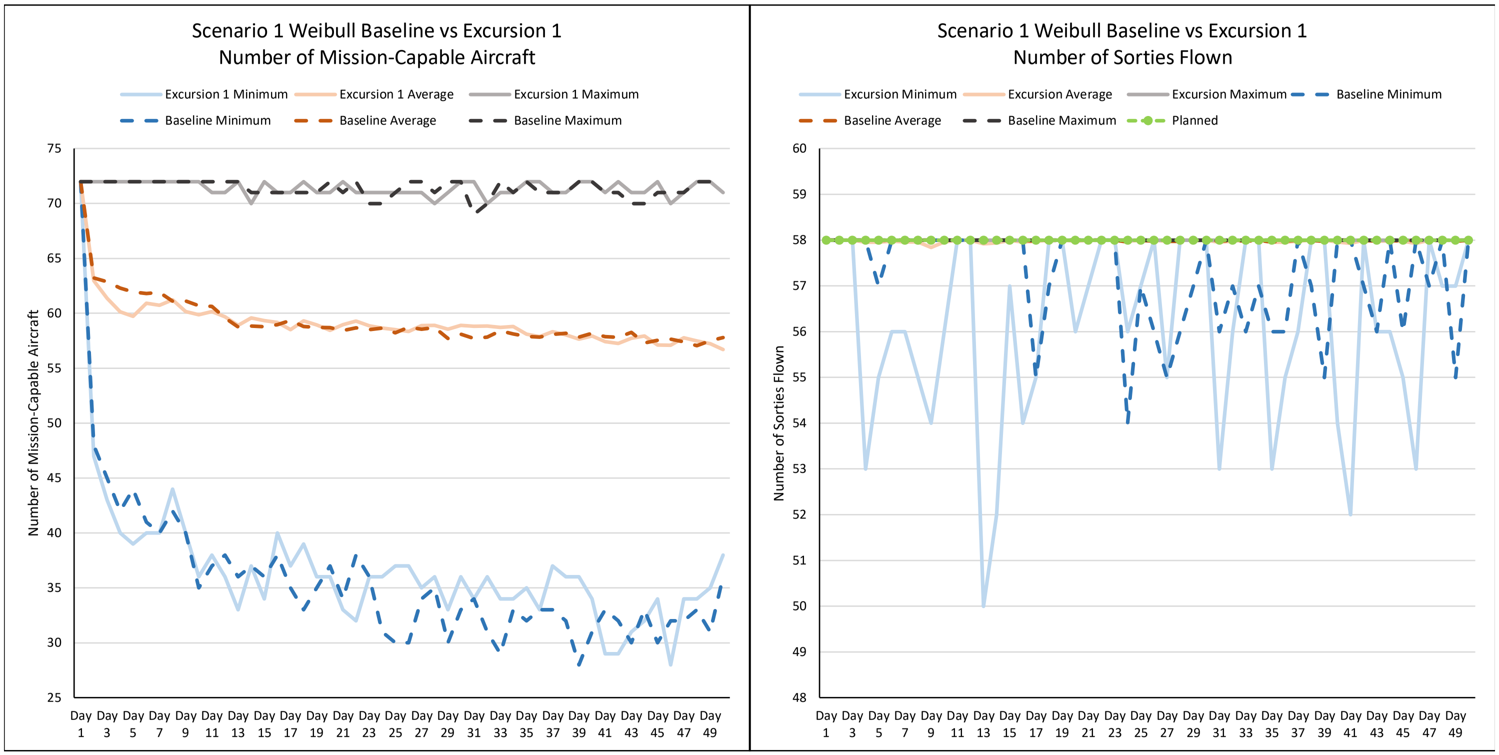


Figure 34. Scenario 1 Weibull Baseline versus Excursion 1 Number of MC Aircraft and Sorties Flown

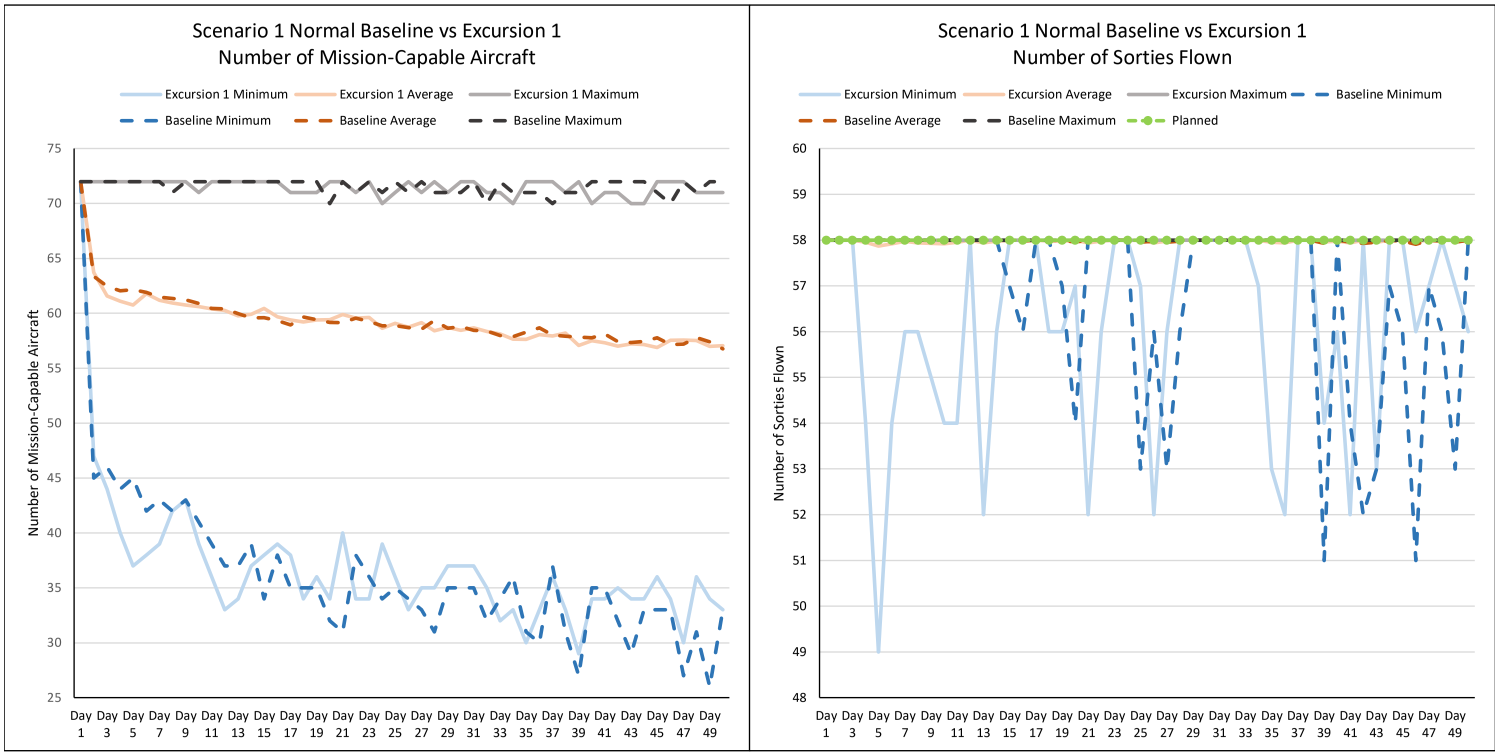


Figure 35. Scenario 1 Normal Baseline versus Excursion 1 Number of MC Aircraft and Sorties Flown

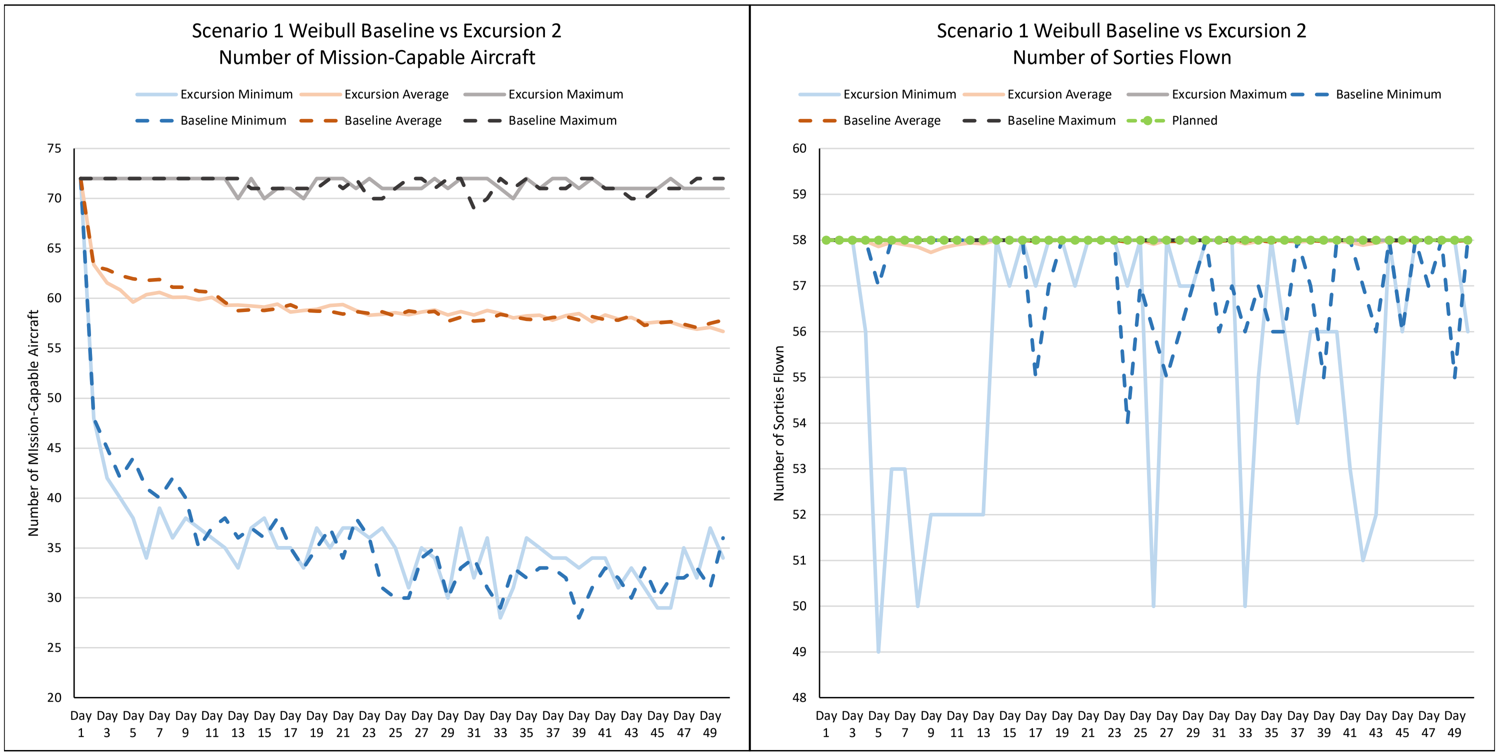


Figure 36. Scenario 1 Weibull Baseline versus Excursion 2 Number of MC Aircraft and Sorties Flown

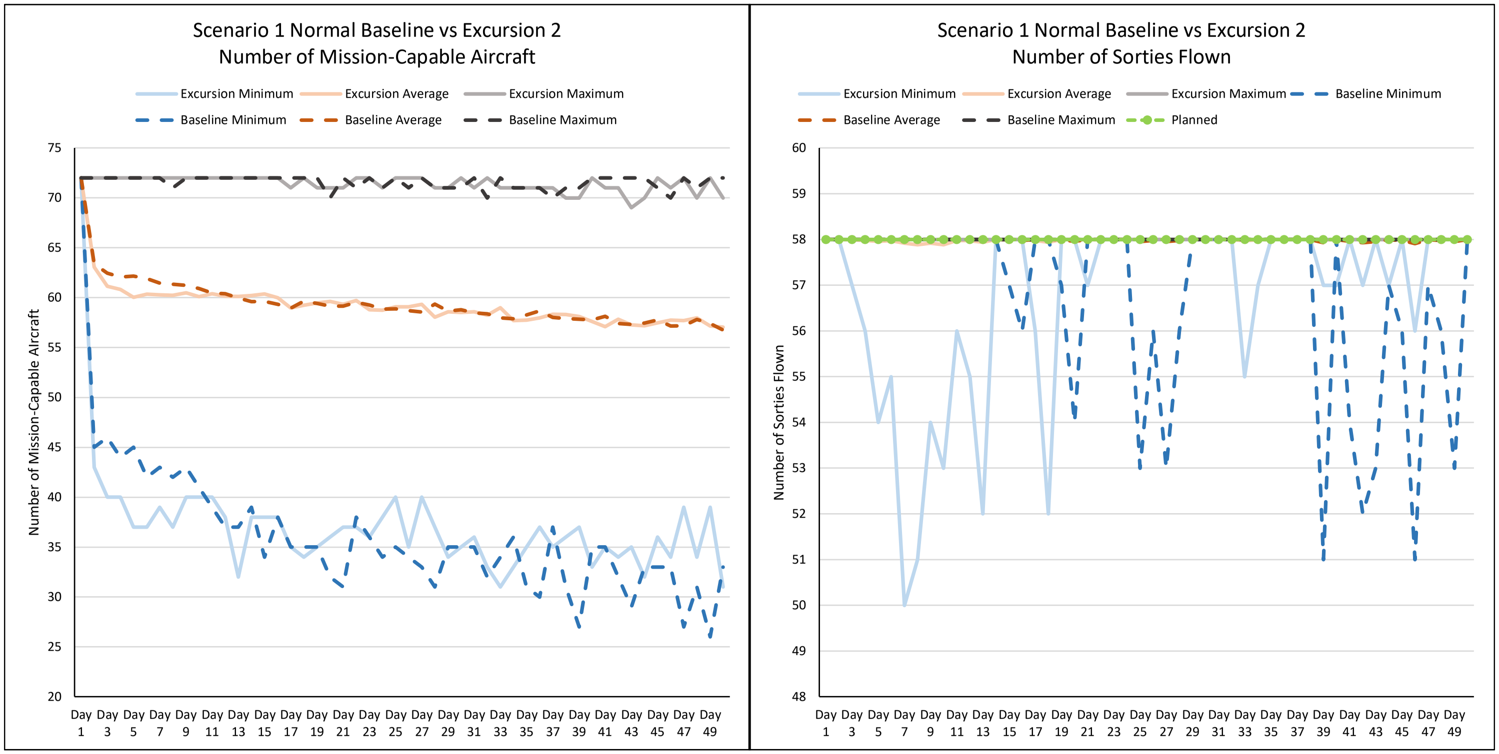


Figure 37. Scenario 1 Normal Baseline versus Excursion 2 Number of MC Aircraft and Sorties Flown

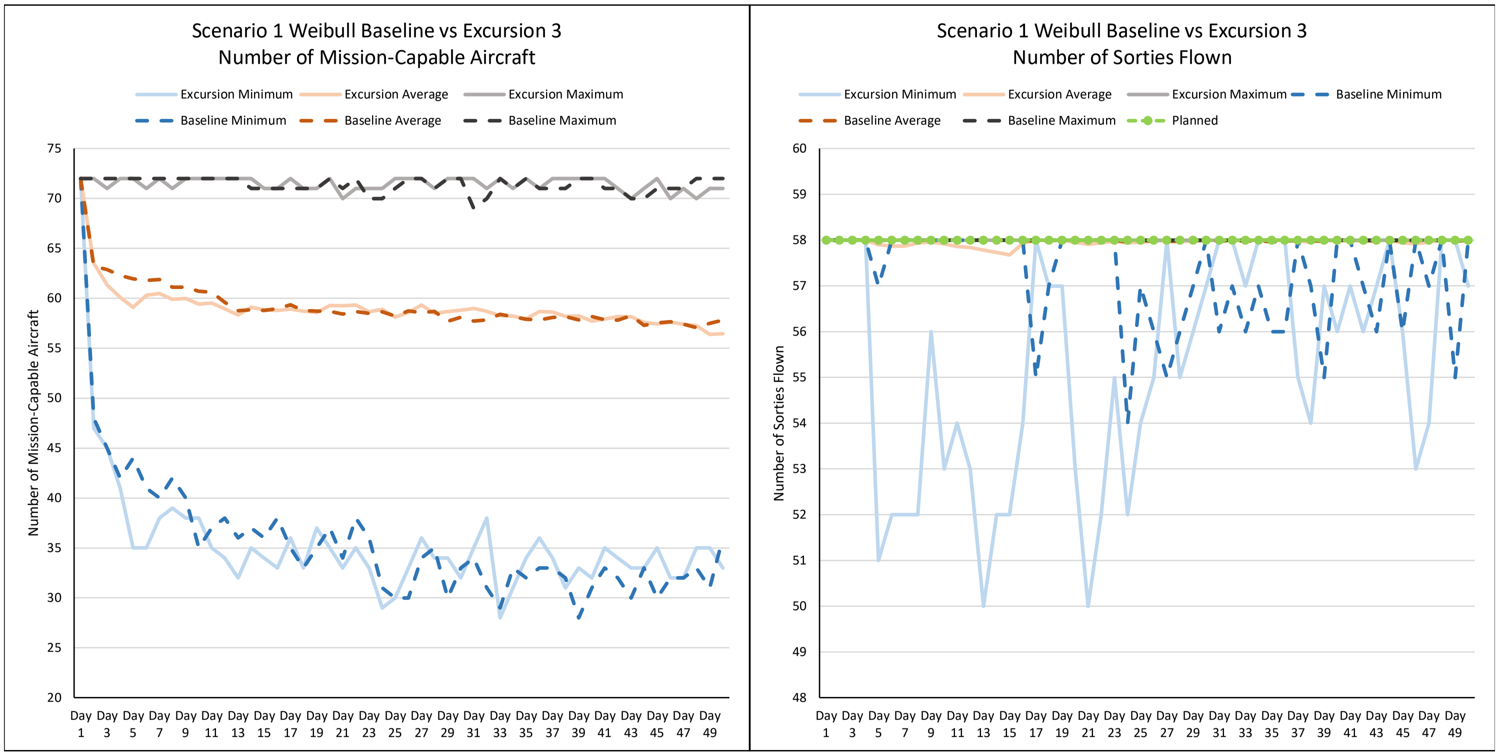


Figure 38. Scenario 1 Weibull Baseline versus Excursion 3 Number of MC Aircraft and Sorties Flown

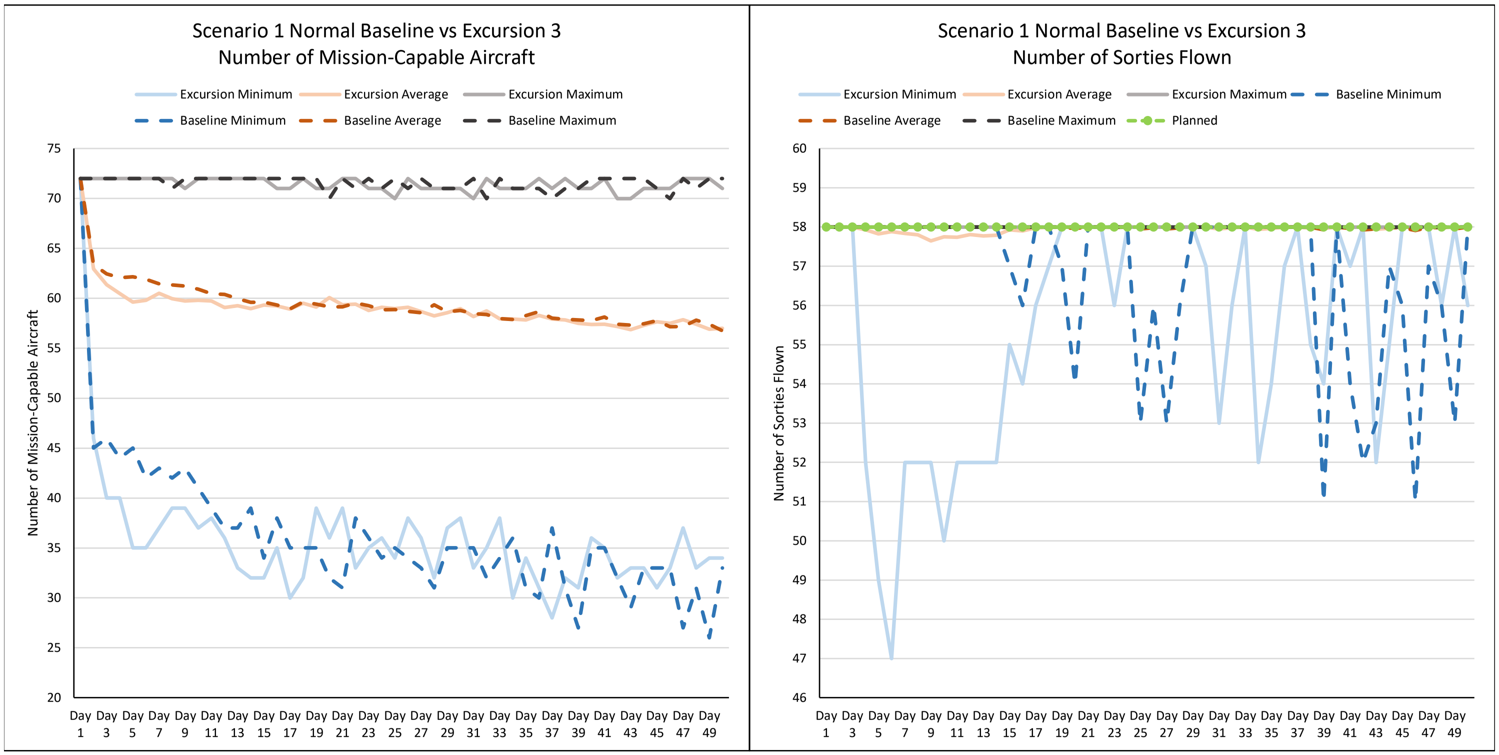


Figure 39. Scenario 1 Normal Baseline versus Excursion 3 Number of MC Aircraft and Sorties Flown

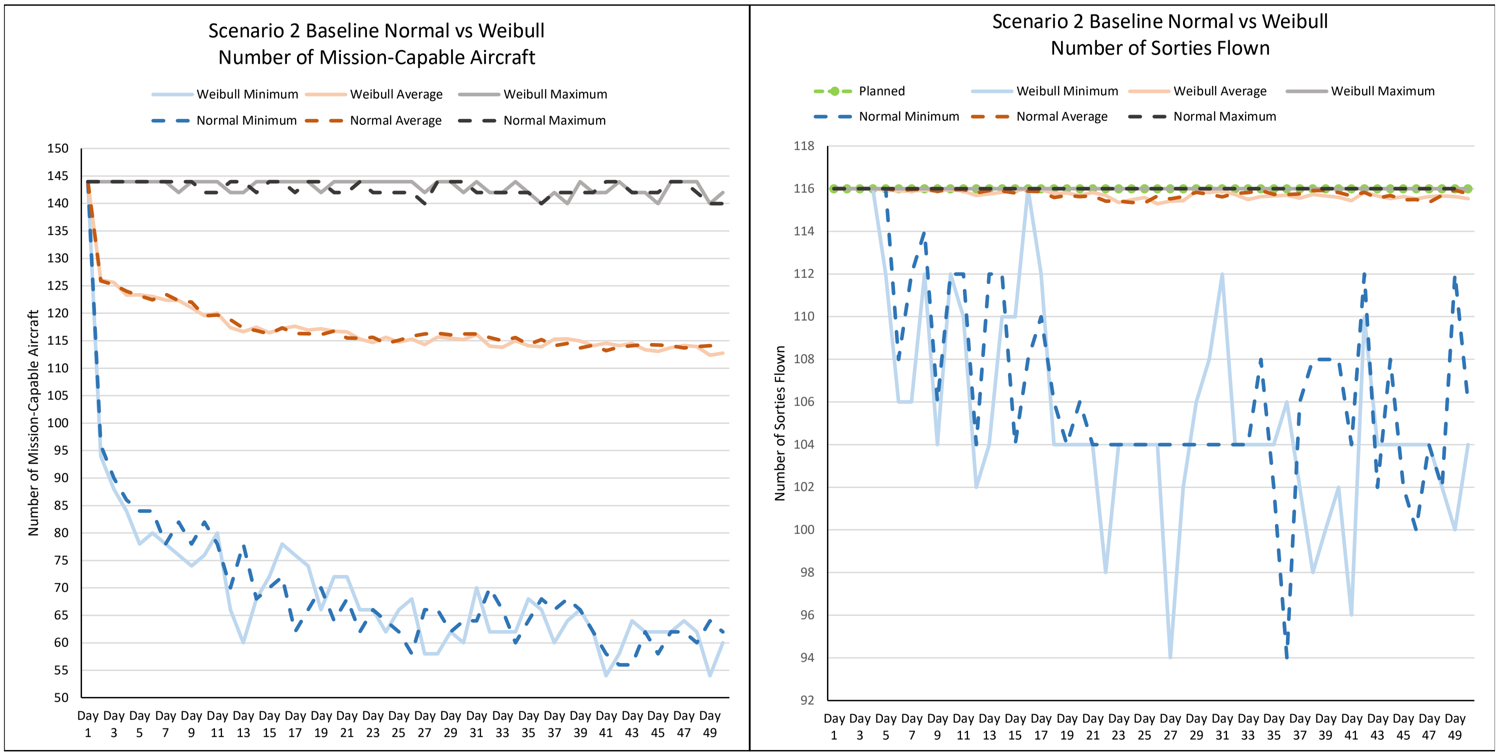


Figure 40. Scenario 2 Baseline Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

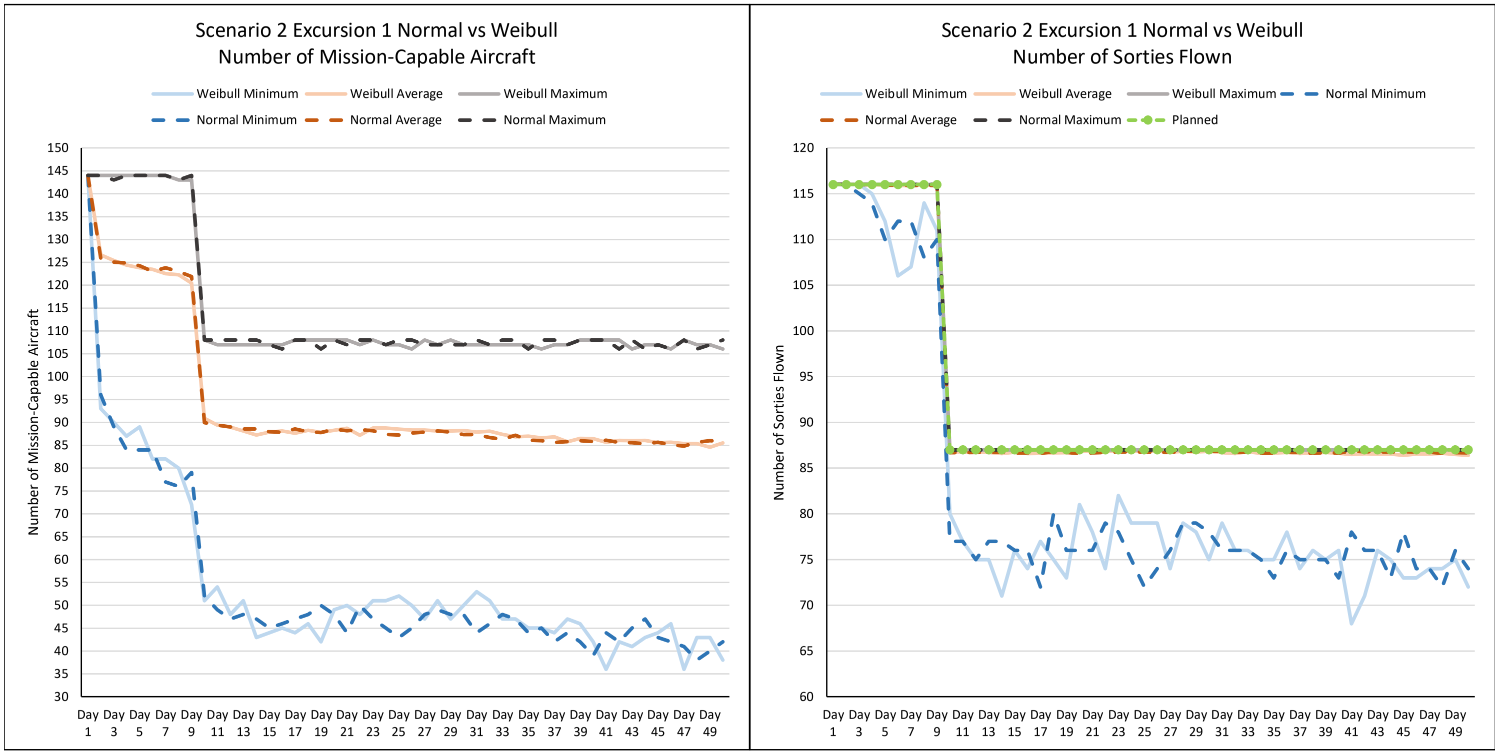


Figure 41. Scenario 2 Excursion 1 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

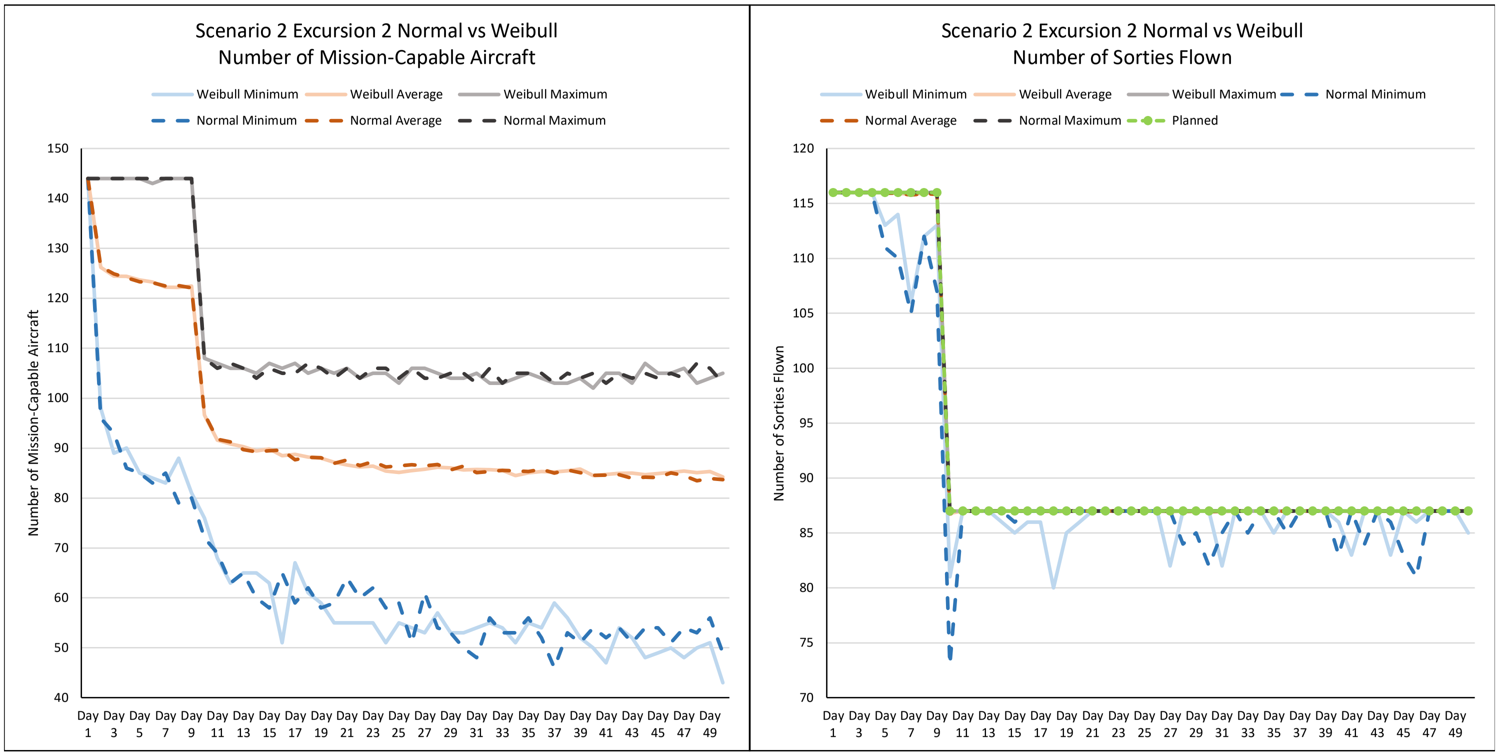


Figure 42. Scenario 2 Excursion 2 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

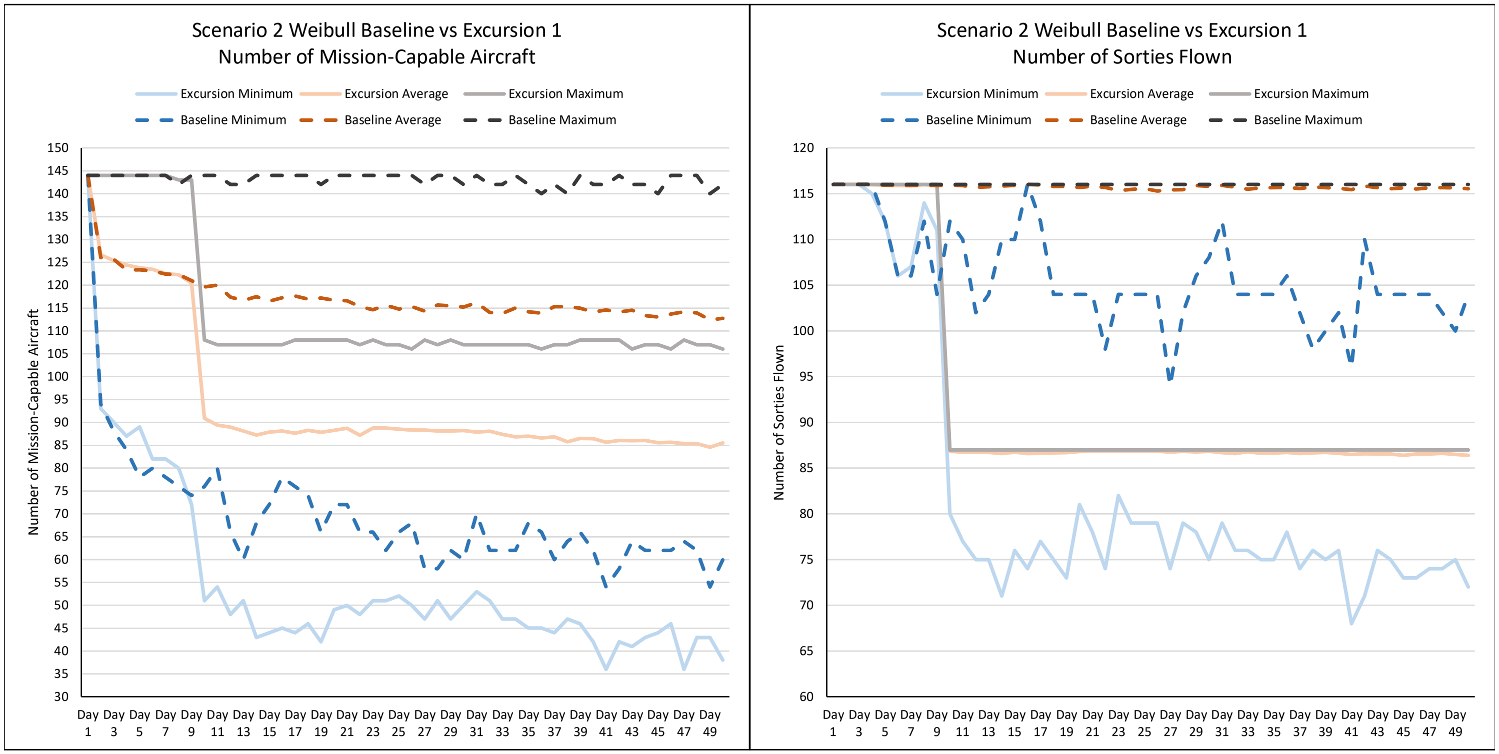


Figure 43. Scenario 2 Weibull Baseline versus Excursion 1 Number of MC Aircraft and Sorties Flown

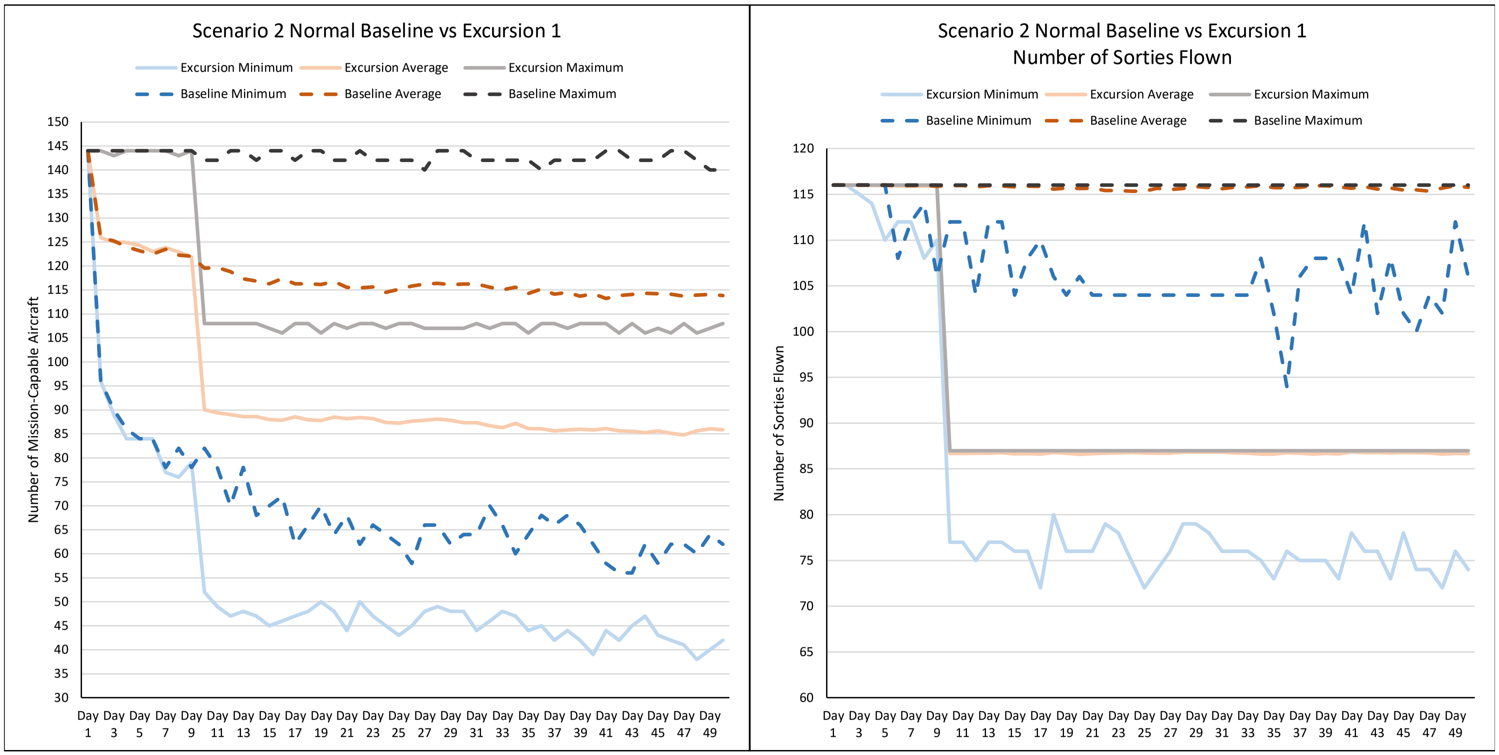


Figure 44. Scenario 2 Normal Baseline versus Excursion 1 Number of MC Aircraft and Sorties Flown

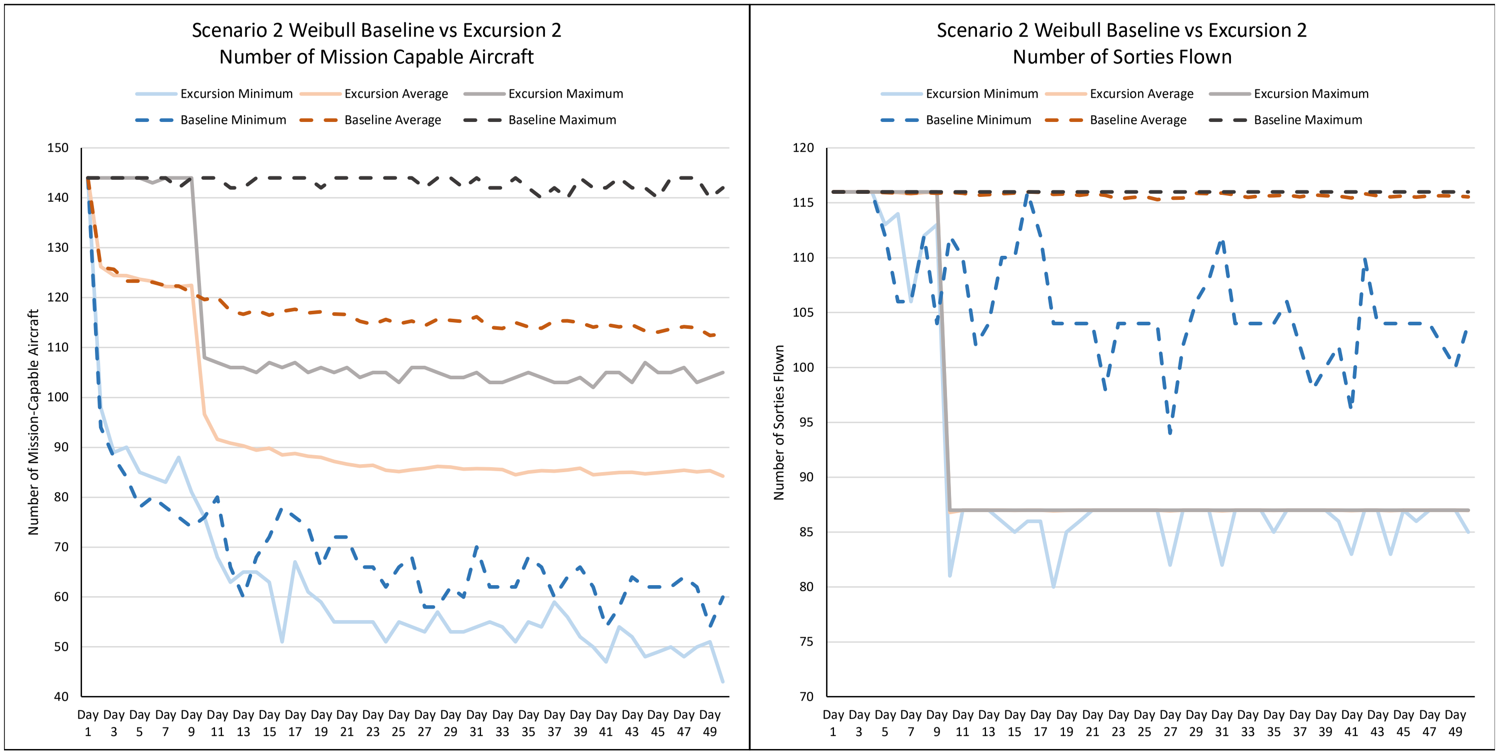


Figure 45. Scenario 2 Weibull Baseline versus Excursion 2 Number of MC Aircraft and Sorties Flown

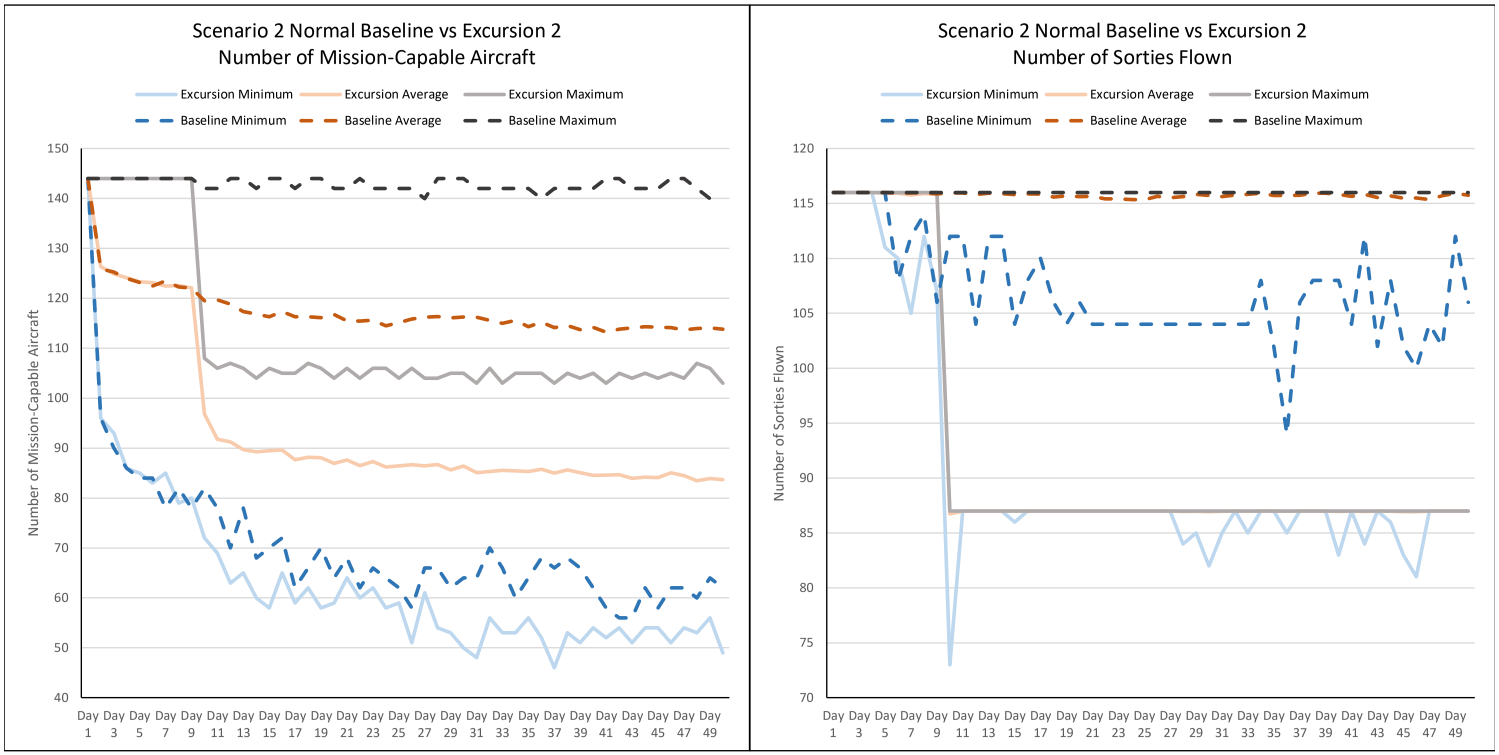


Figure 46. Scenario 2 Normal Baseline versus Excursion 2 Number of MC Aircraft and Sorties Flown

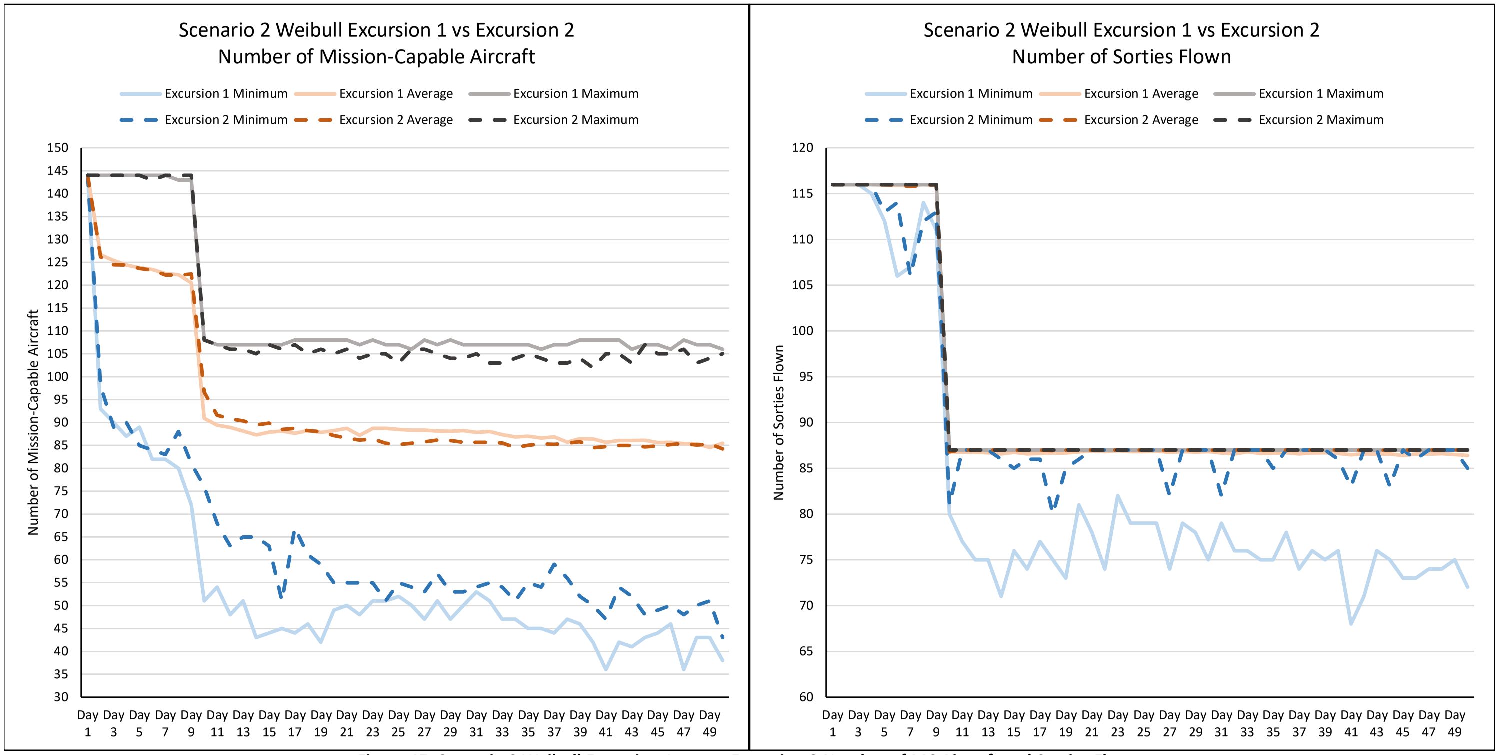


Figure 47. Scenario 2 Weibull Excursion 1 versus Excursion 2 Number of MC Aircraft and Sorties Flown

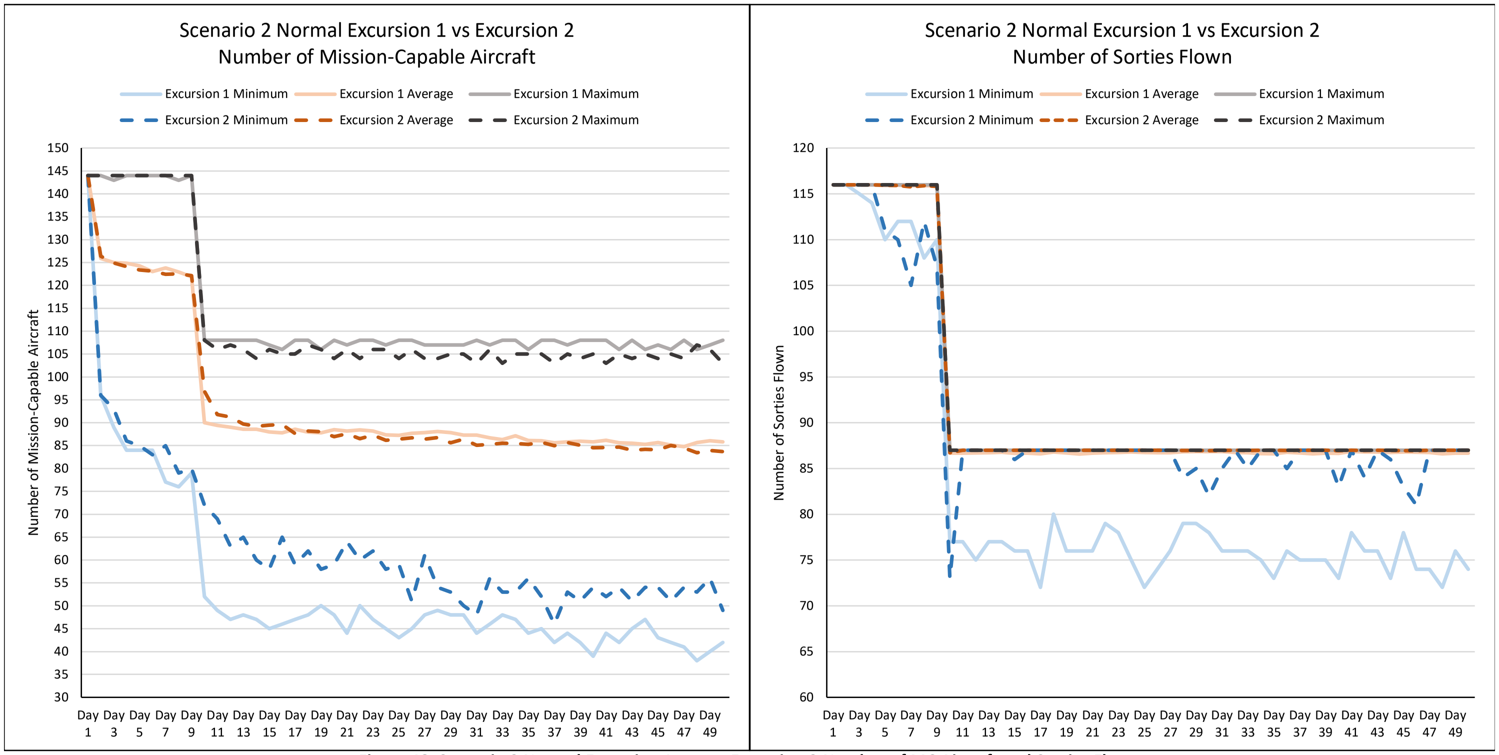


Figure 48. Scenario 2 Normal Excursion 1 versus Excursion 2 Number of MC Aircraft and Sorties Flown

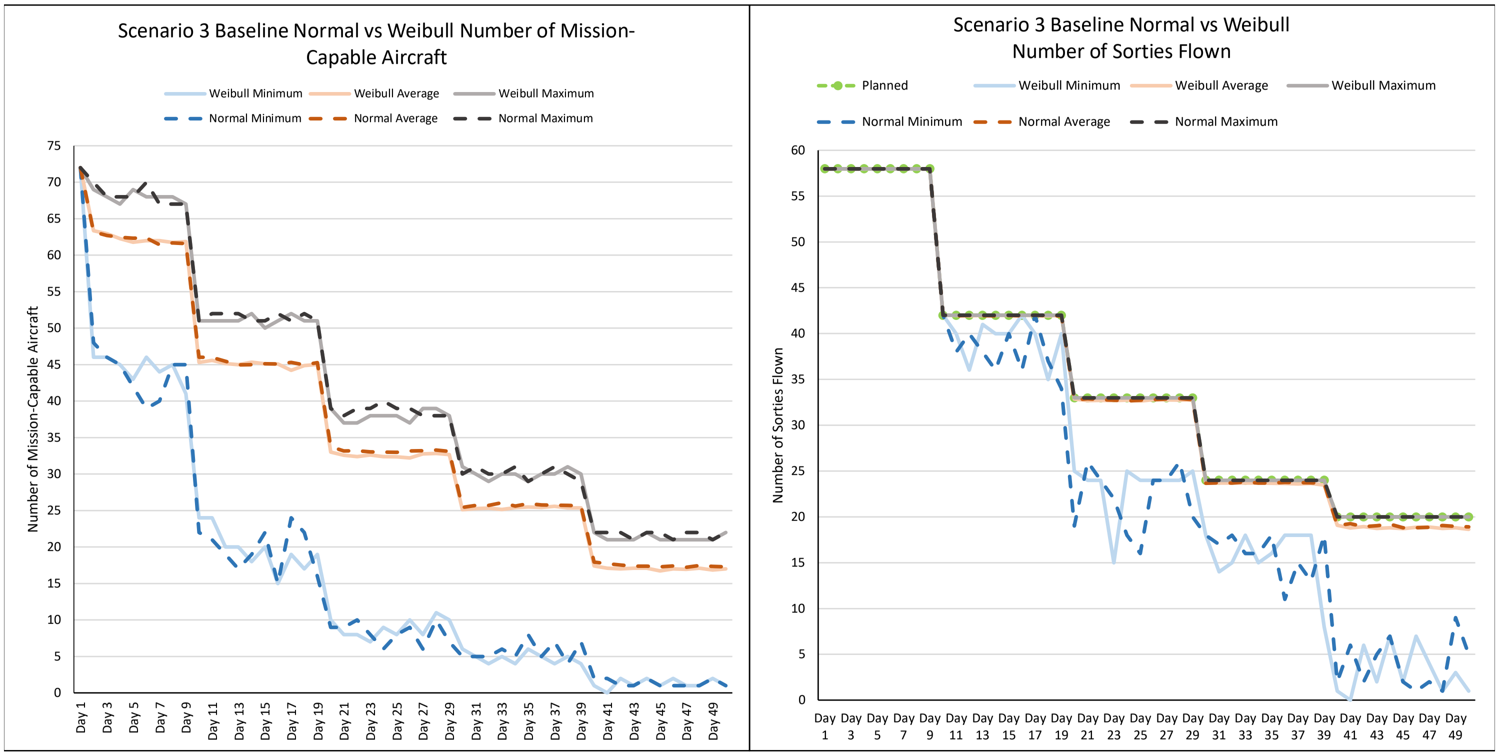


Figure 49. Scenario 3 Baseline Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

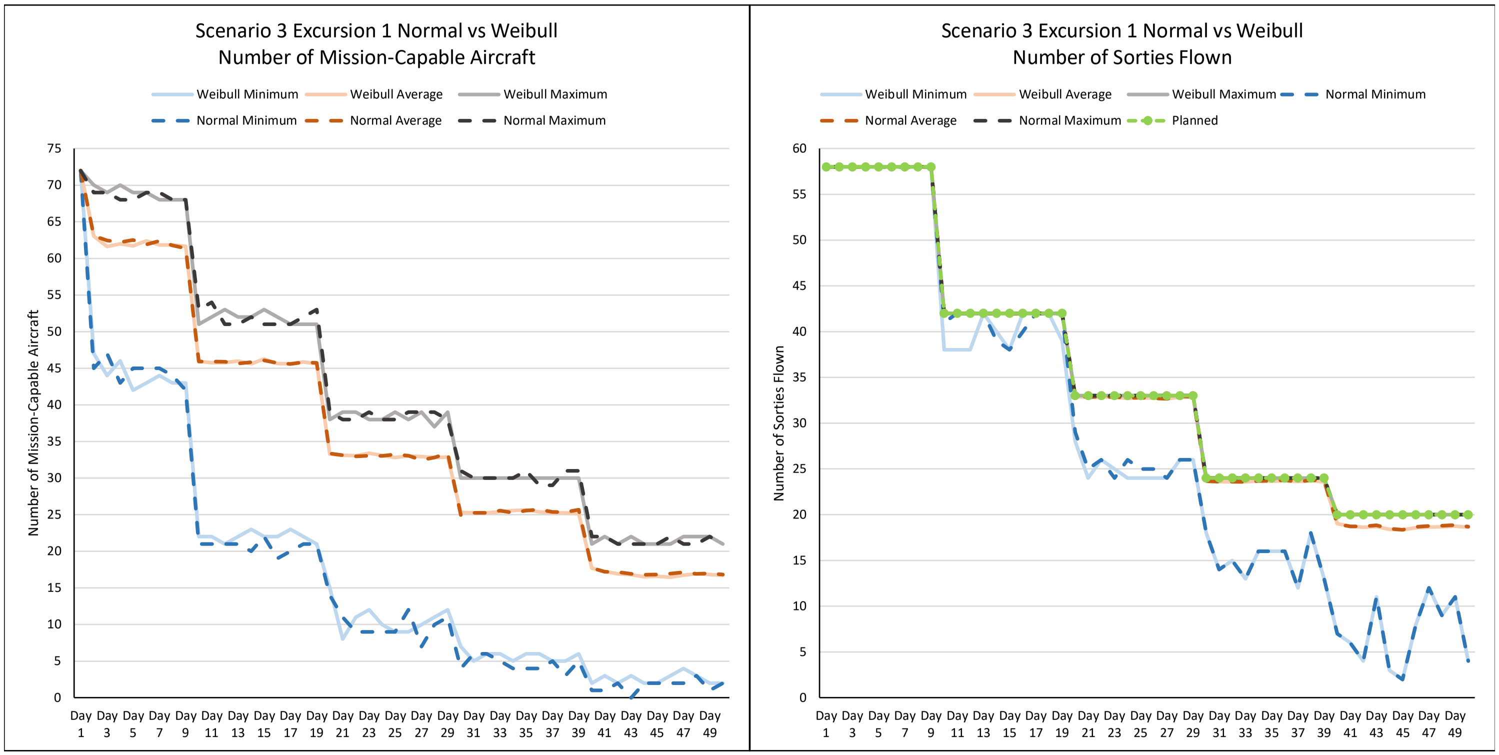


Figure 50. Scenario 3 Excursion 1 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

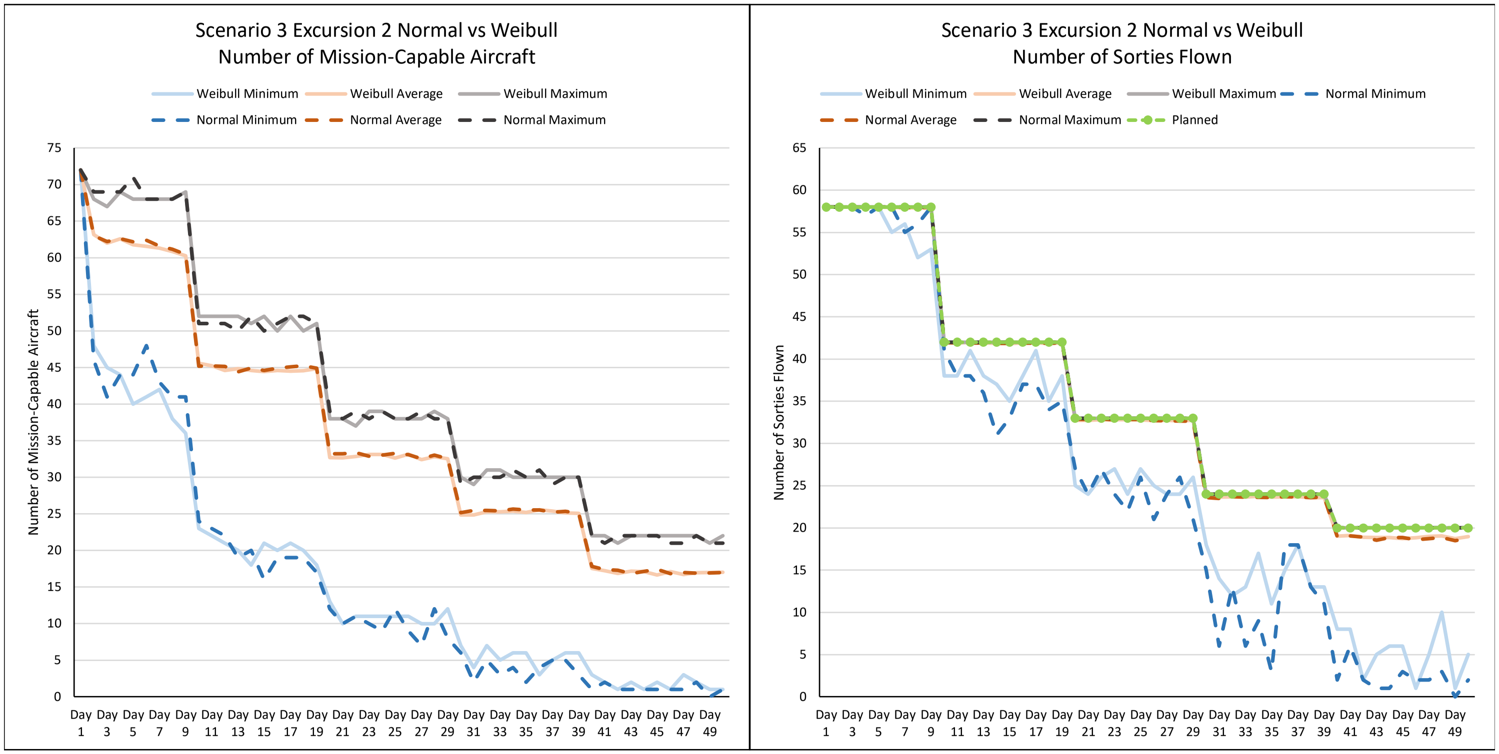


Figure 51. Scenario 3 Excursion 2 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

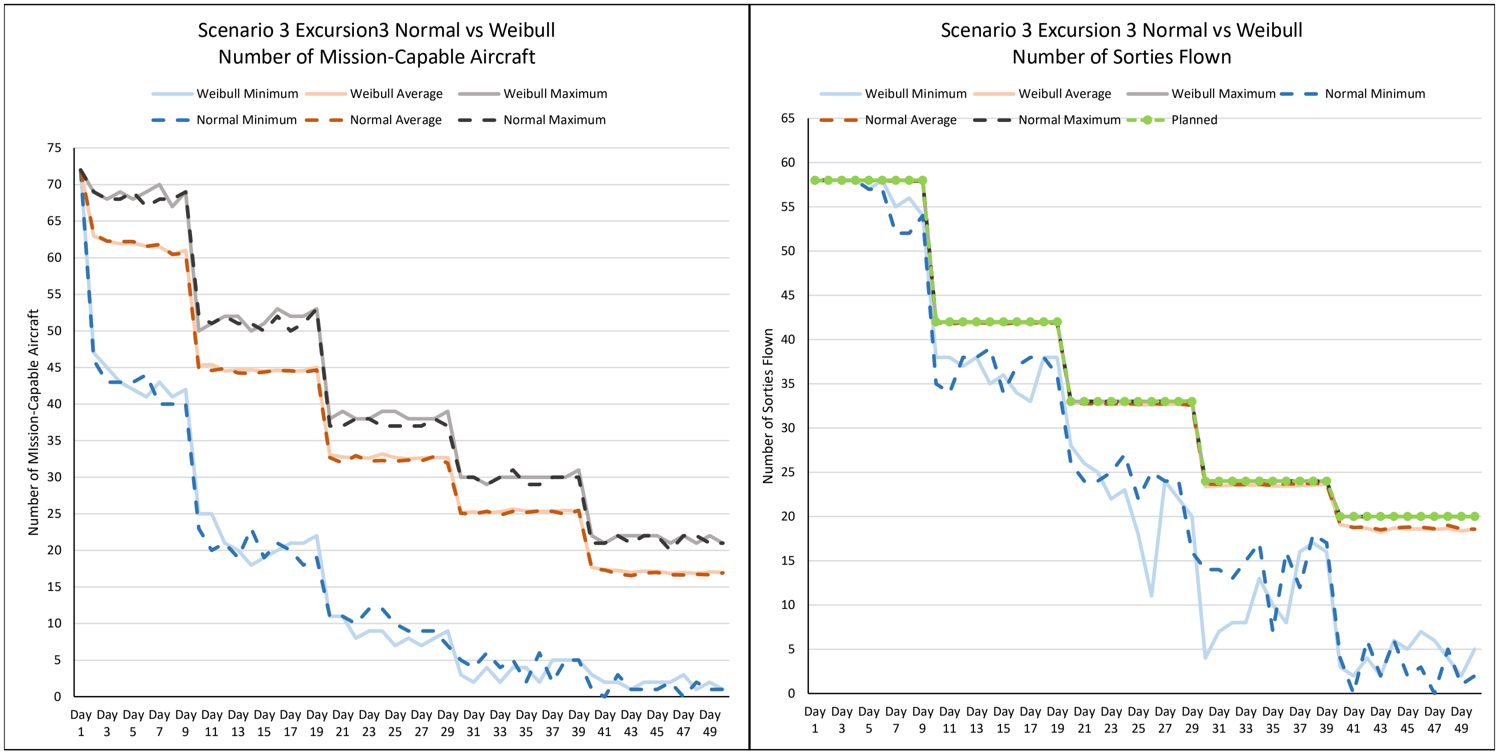


Figure 52. Scenario 3 Excursion 3 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

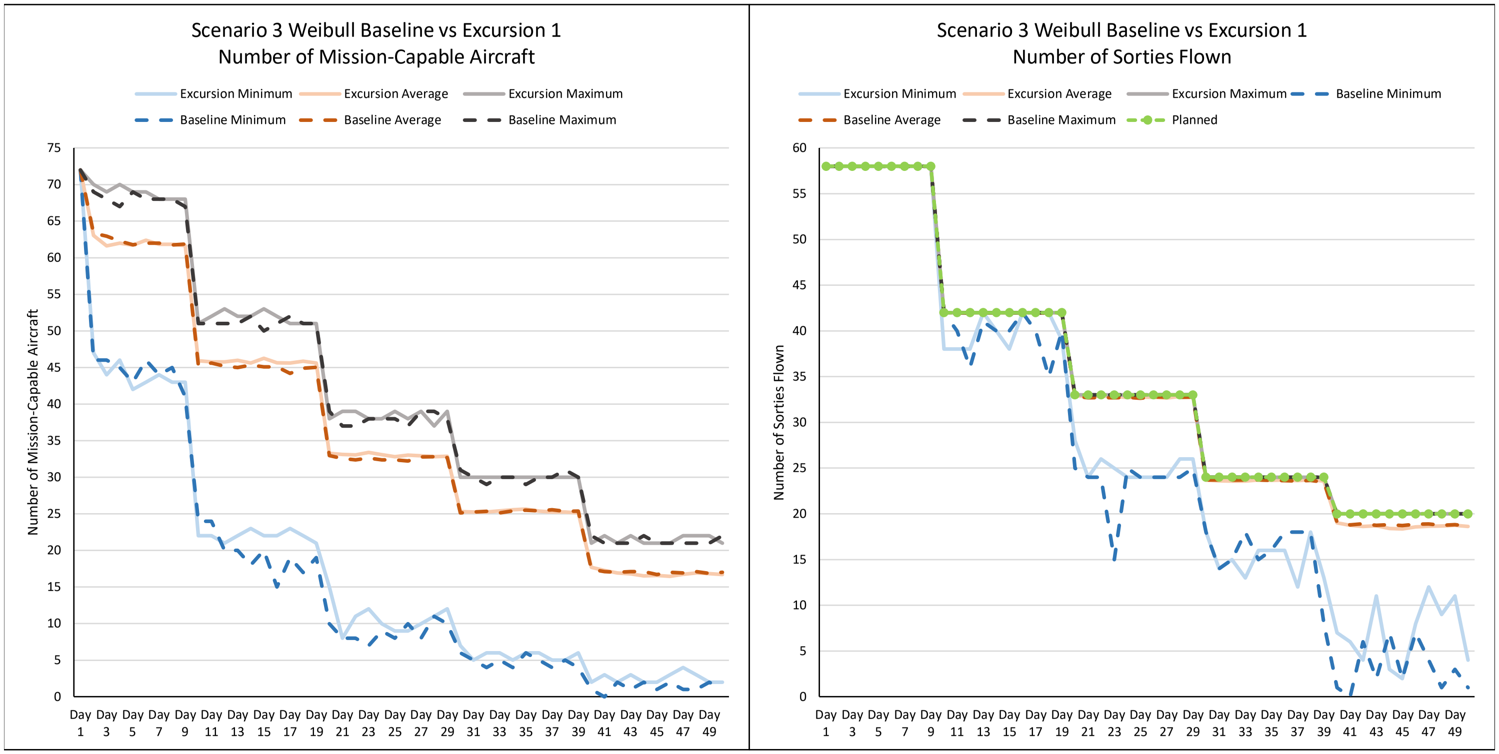


Figure 53. Scenario 3 Weibull Baseline versus Excursion 1 Number of MC Aircraft and Sorties Flown

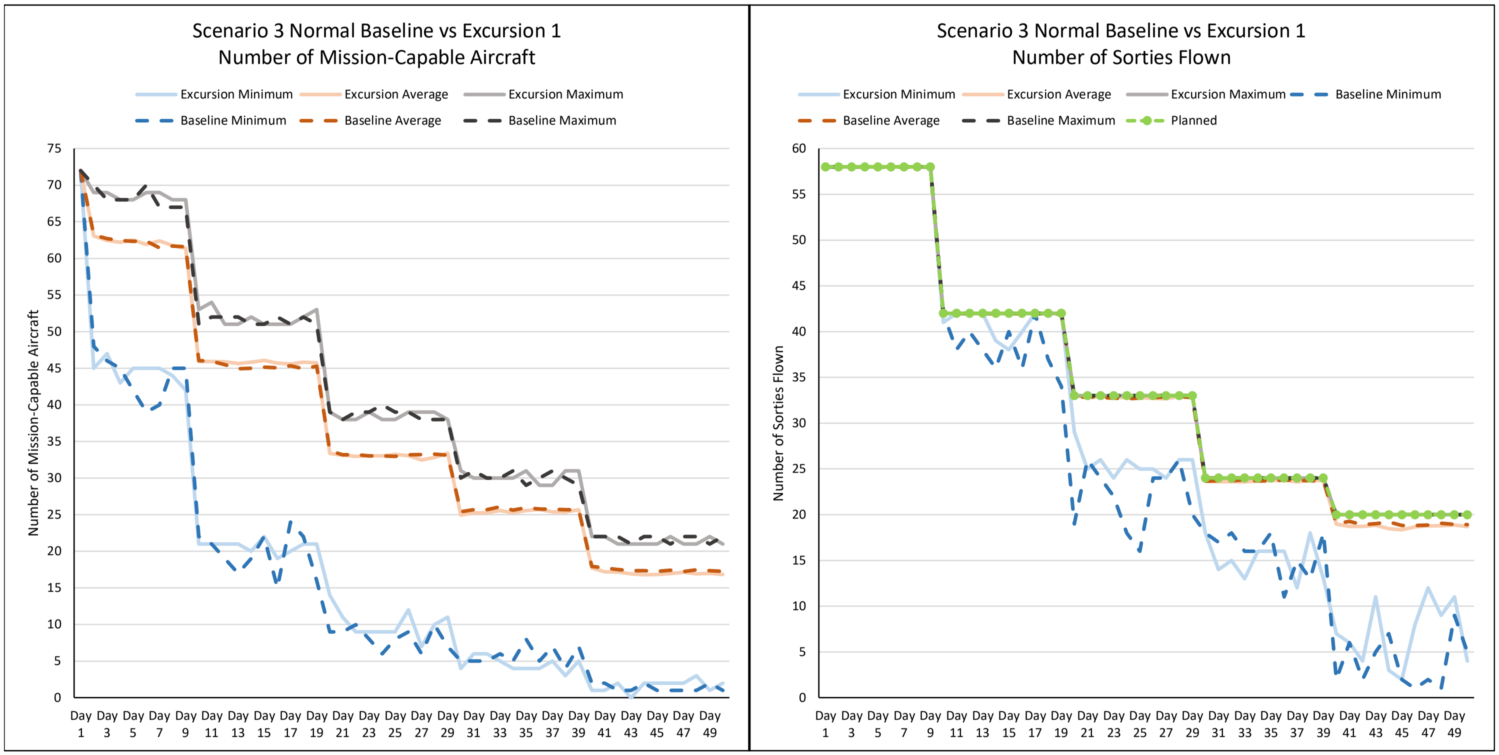


Figure 54. Scenario 3 Normal Baseline versus Excursion 1 Number of MC Aircraft and Sorties Flown

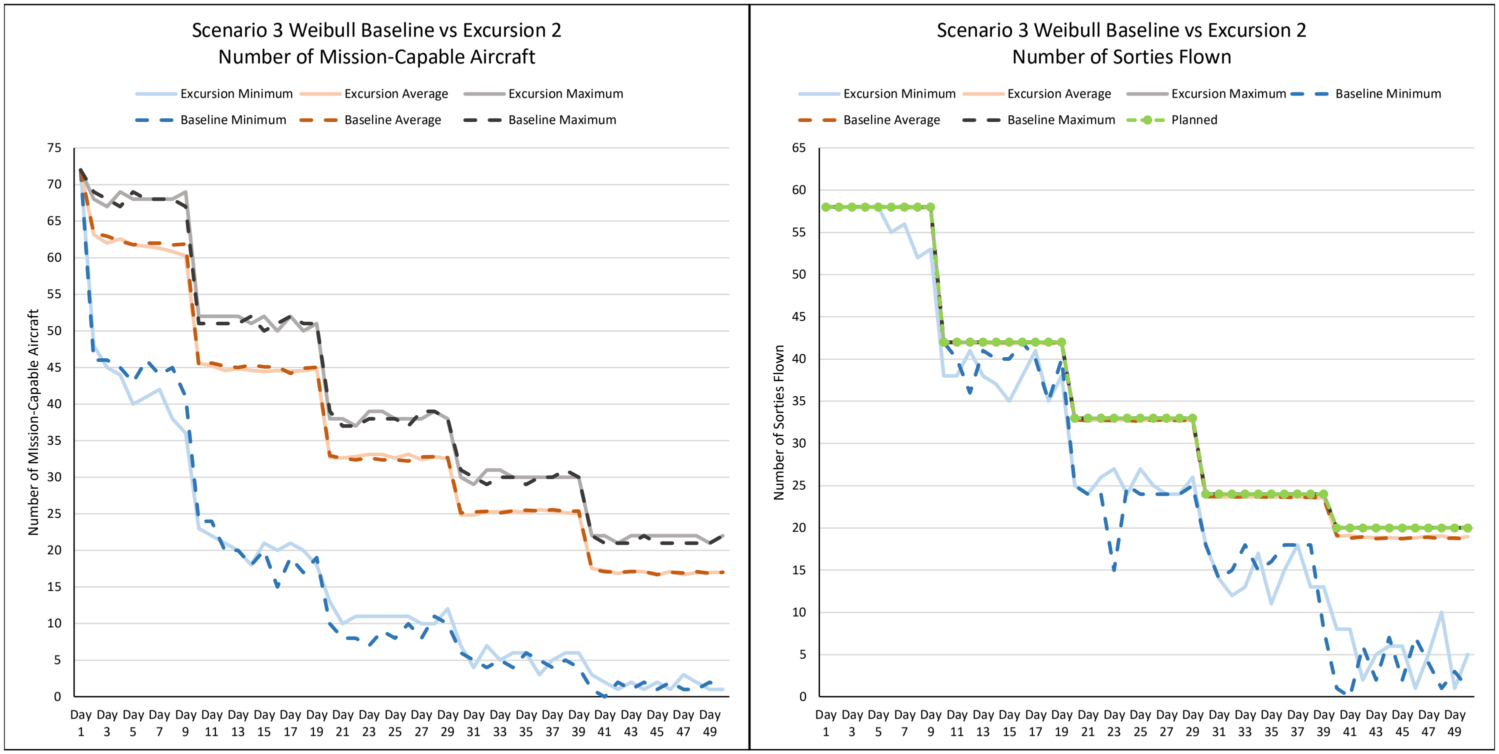


Figure 55. Scenario 3 Weibull Baseline versus Excursion 2 Number of MC Aircraft and Sorties Flown

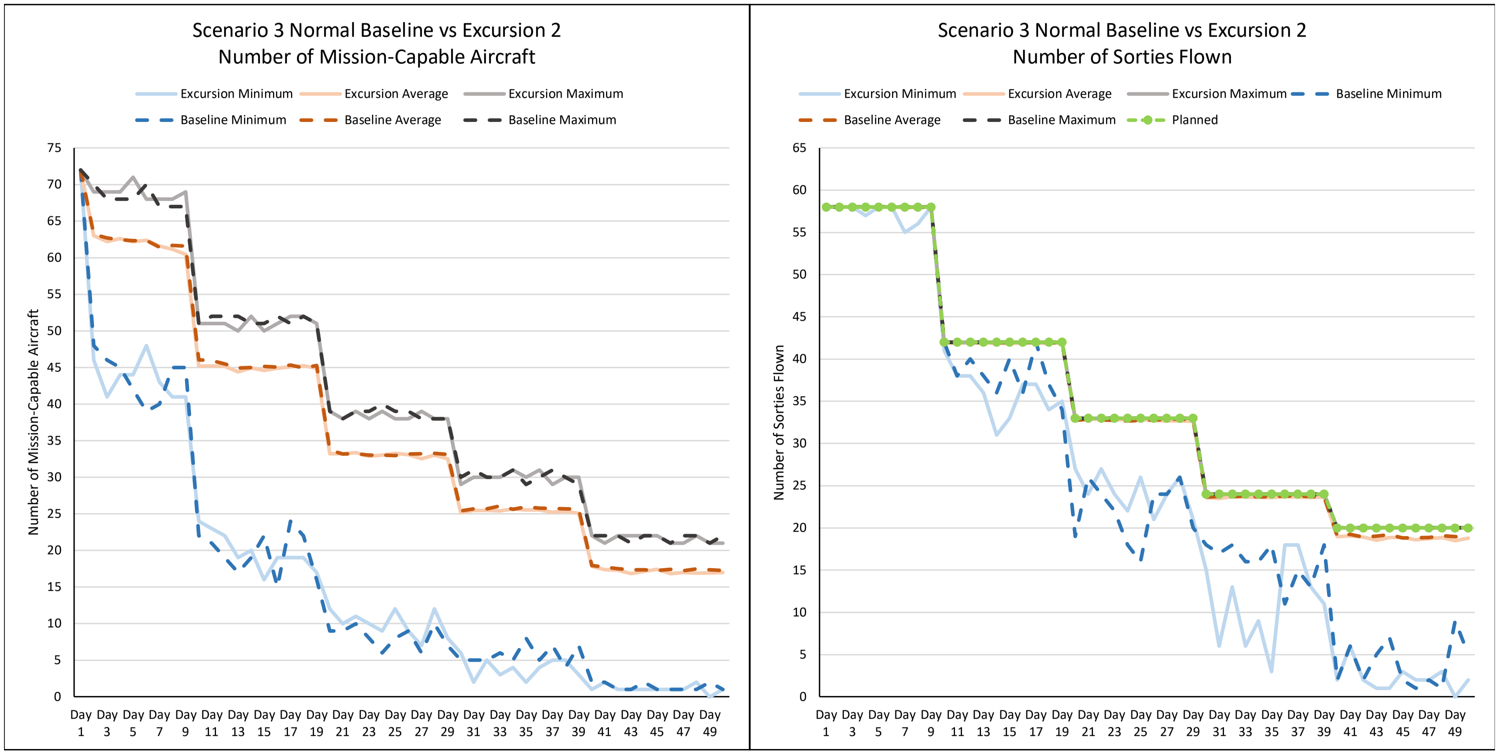


Figure 56. Scenario 3 Normal Baseline versus Excursion 2 Number of MC Aircraft and Sorties Flown

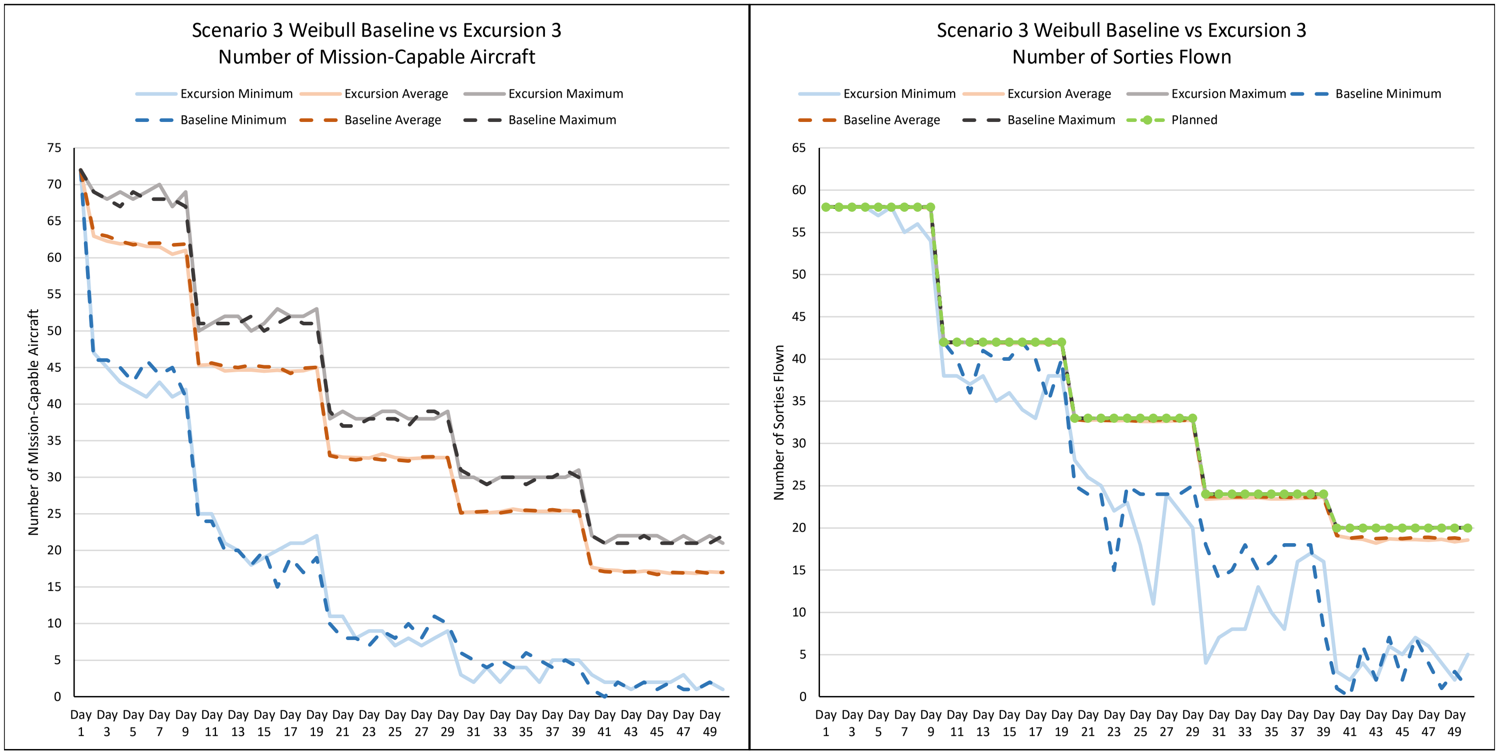


Figure 57. Scenario 3 Weibull Baseline versus Excursion 3 Number of MC Aircraft and Sorties Flown

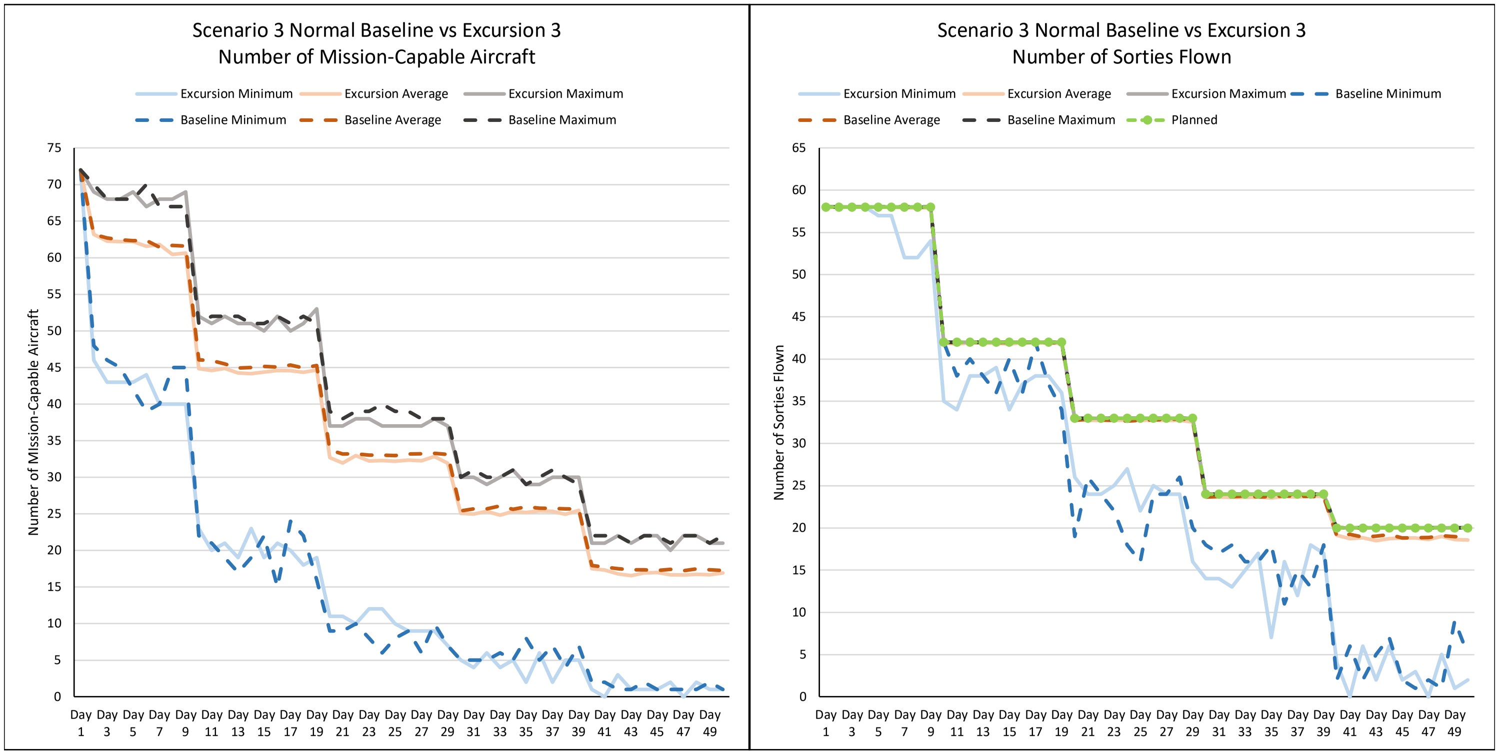


Figure 58. Scenario 3 Normal Baseline versus Excursion 3 Number of MC Aircraft and Sorties Flown

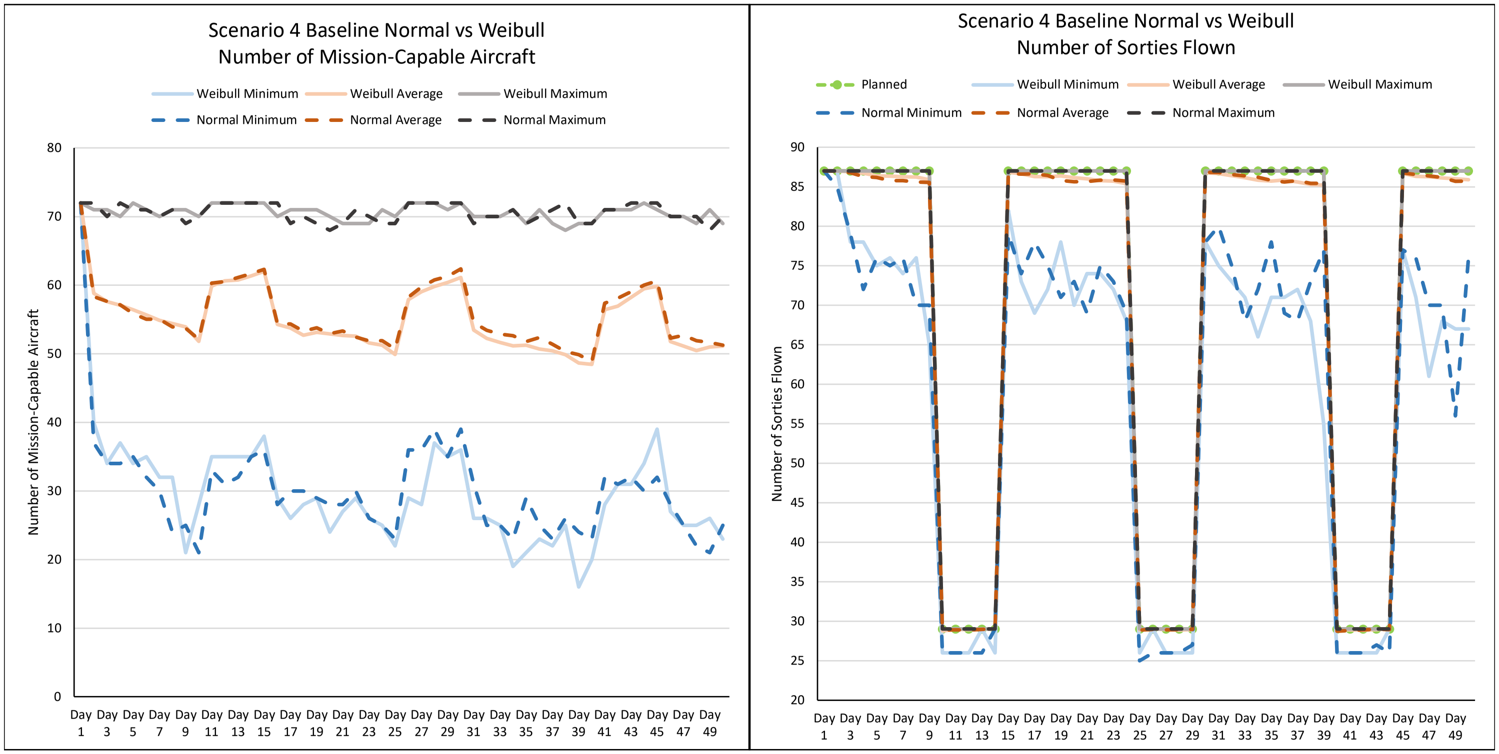


Figure 59. Scenario 4 Baseline Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

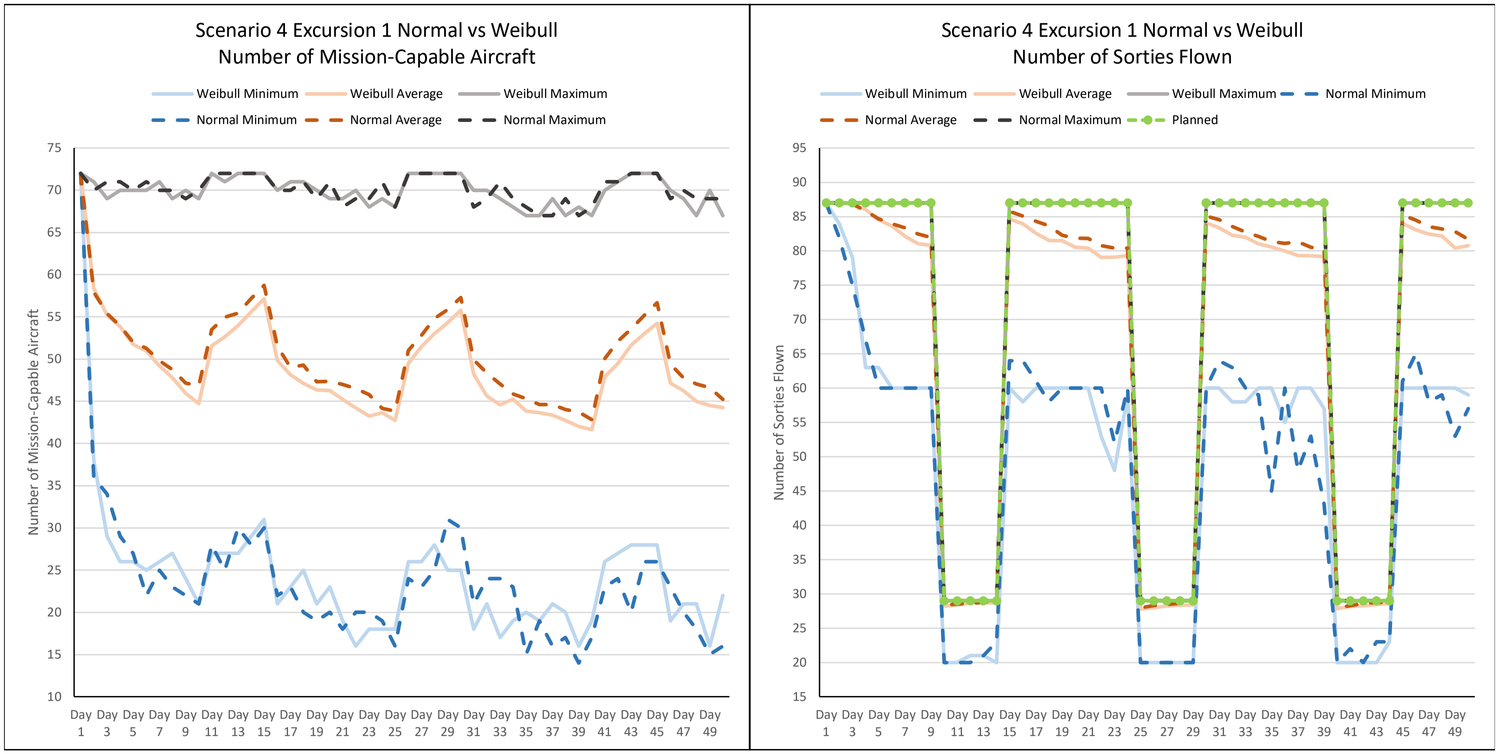


Figure 60. Scenario 4 Excursion 1 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

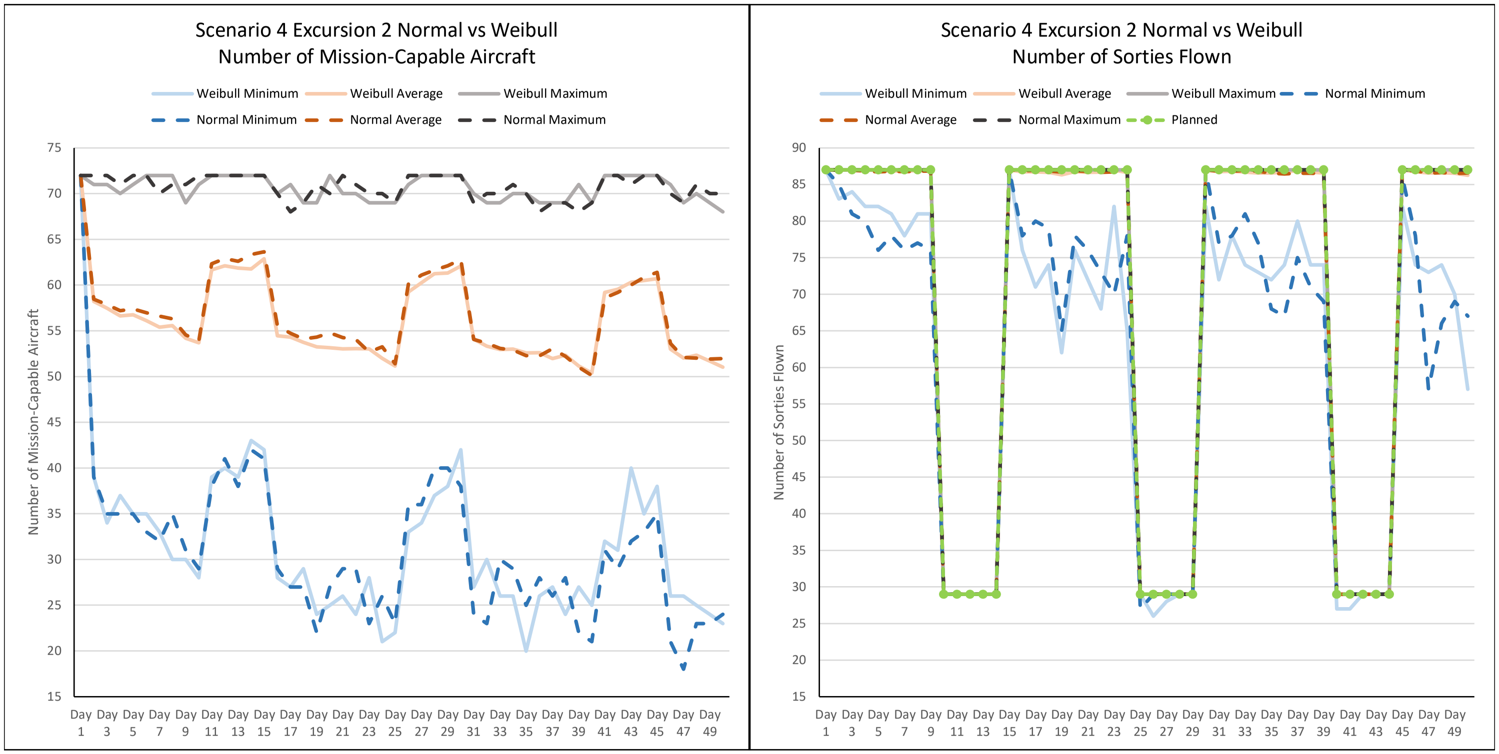


Figure 61. Scenario 4 Excursion 2 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

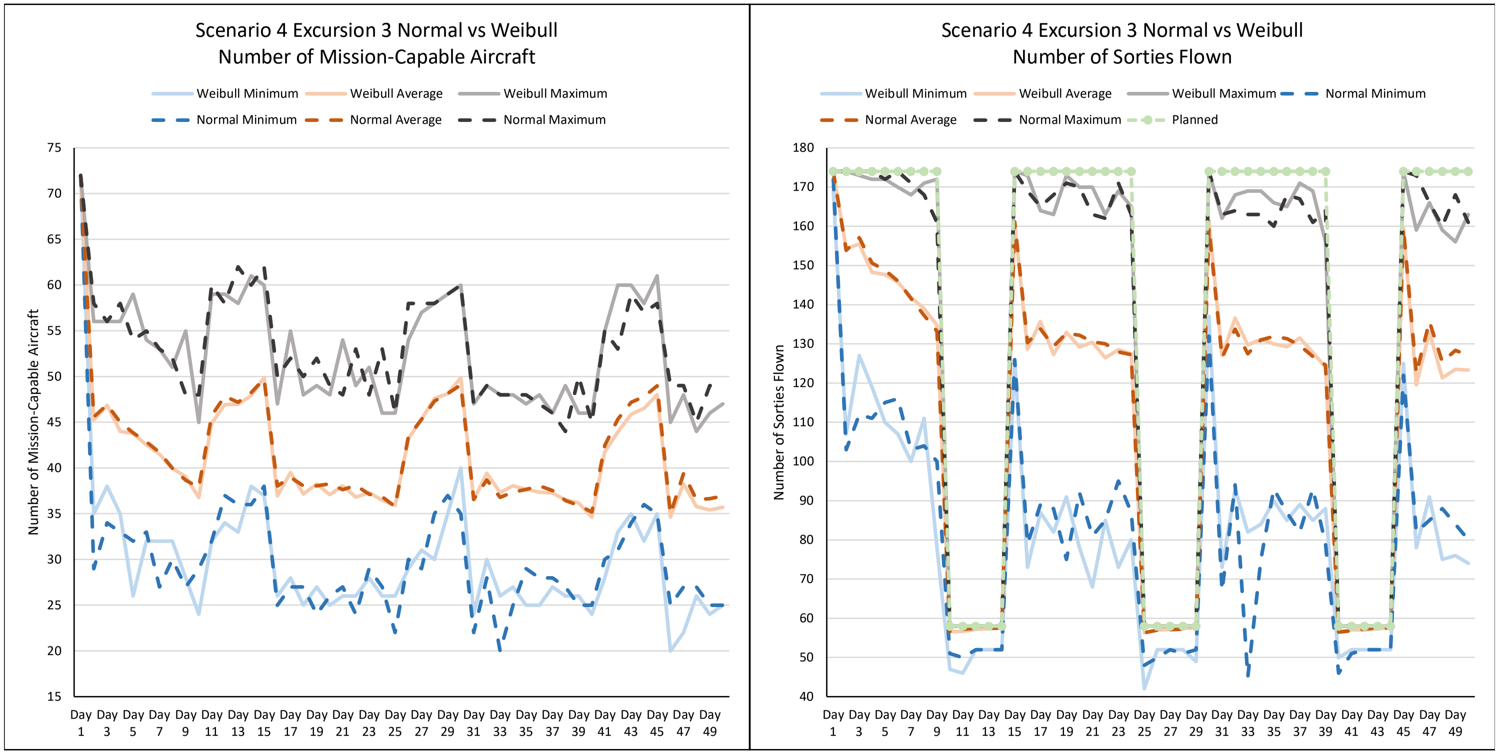


Figure 62. Scenario 4 Excursion 3 Comparison of Normal and Weibull functions for Number of MC Aircraft and Sorties Flown

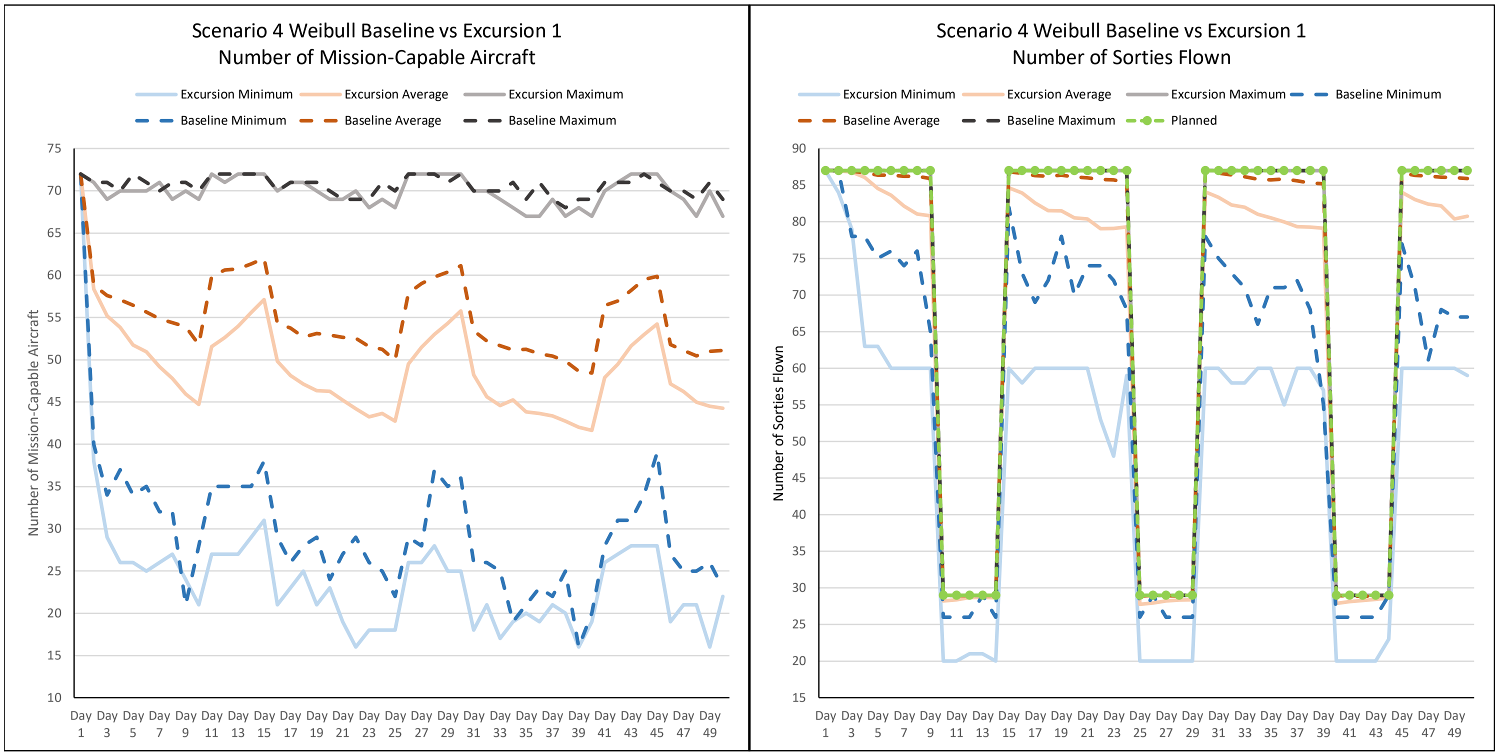


Figure 63. Scenario 4 Weibull Baseline versus Excursion 1 Number of MC Aircraft and Sorties Flown

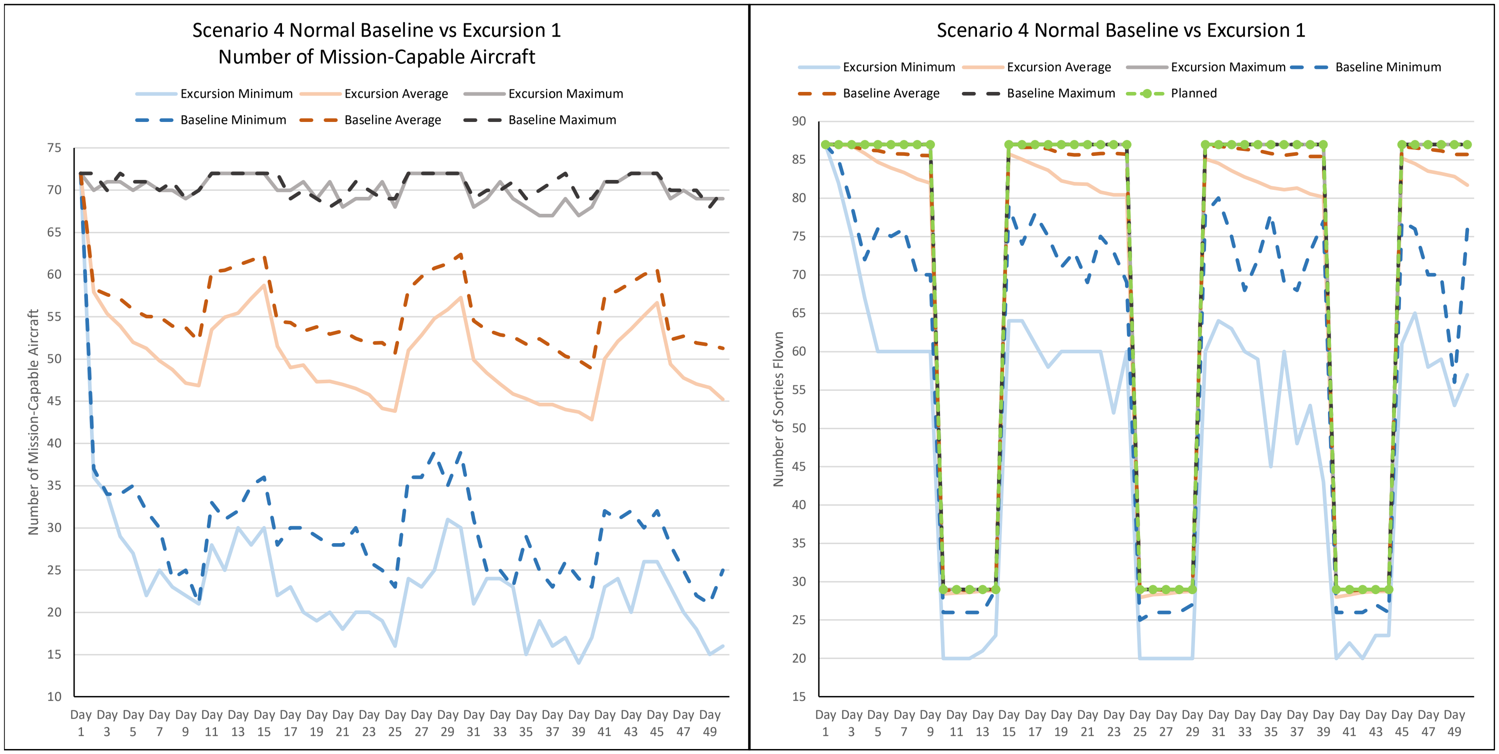
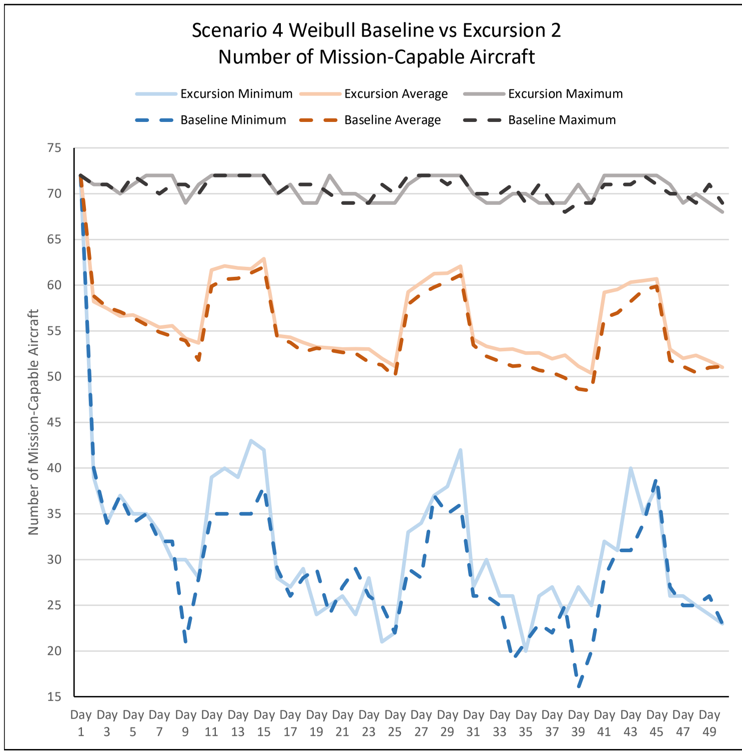


Figure 64. Scenario 4 Normal Baseline versus Excursion 1 Number of MC Aircraft and Sorties Flown



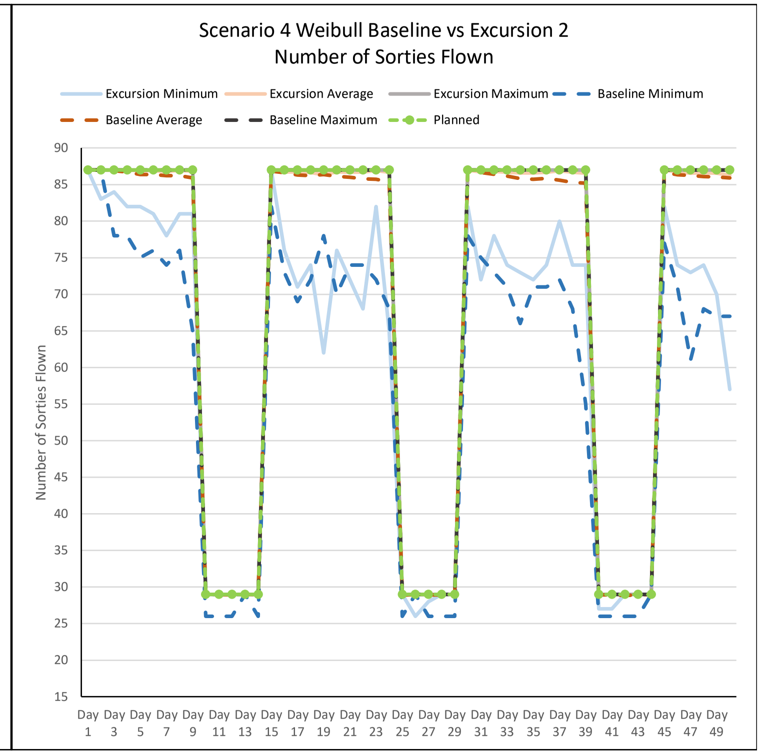


Figure 65. Scenario 4 Weibull Baseline versus Excursion 2 Number of MC Aircraft and Sorties Flown

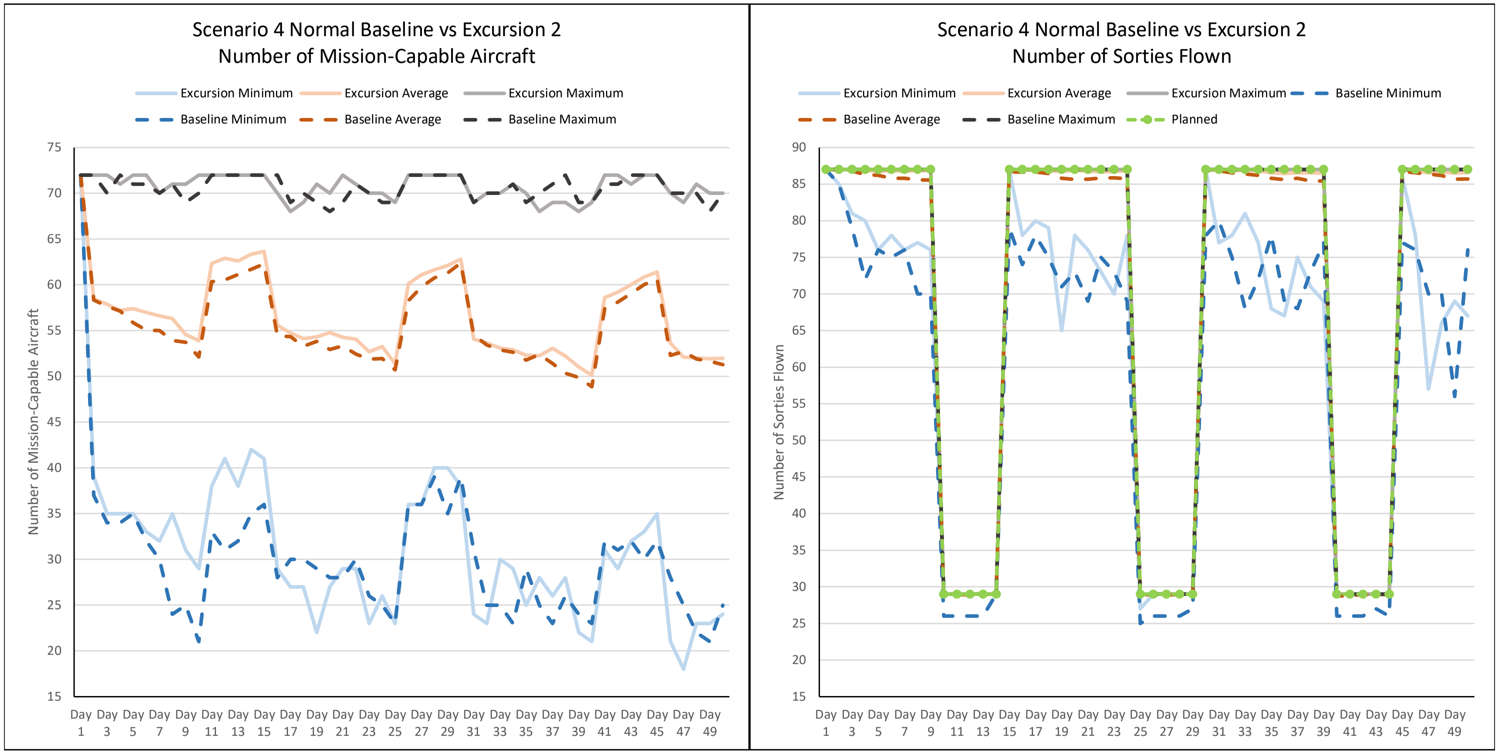


Figure 66. Scenario 4 Normal Baseline versus Excursion 2 Number of MC Aircraft and Sorties Flown

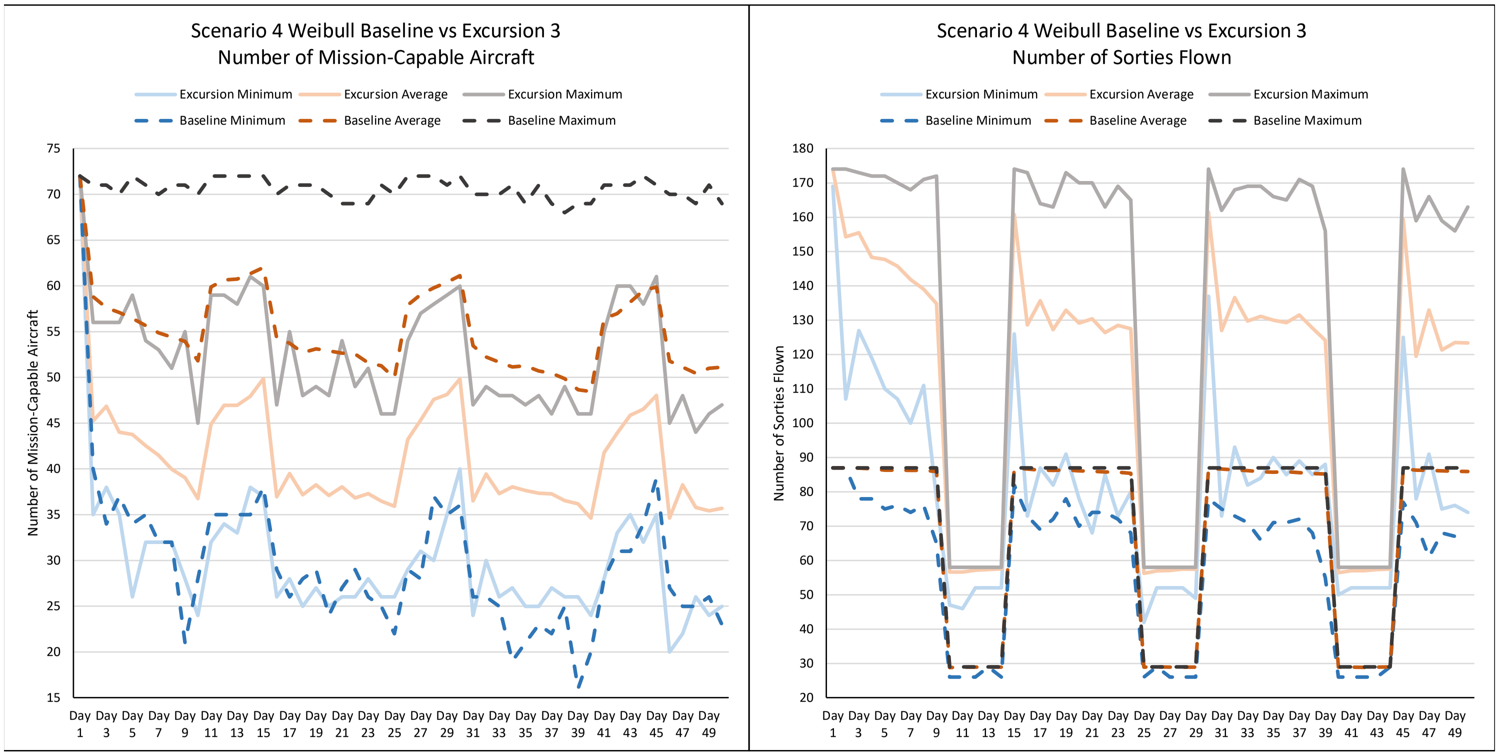


Figure 67. Scenario 4 Weibull Baseline versus Excursion 3 Number of MC Aircraft and Sorties Flown

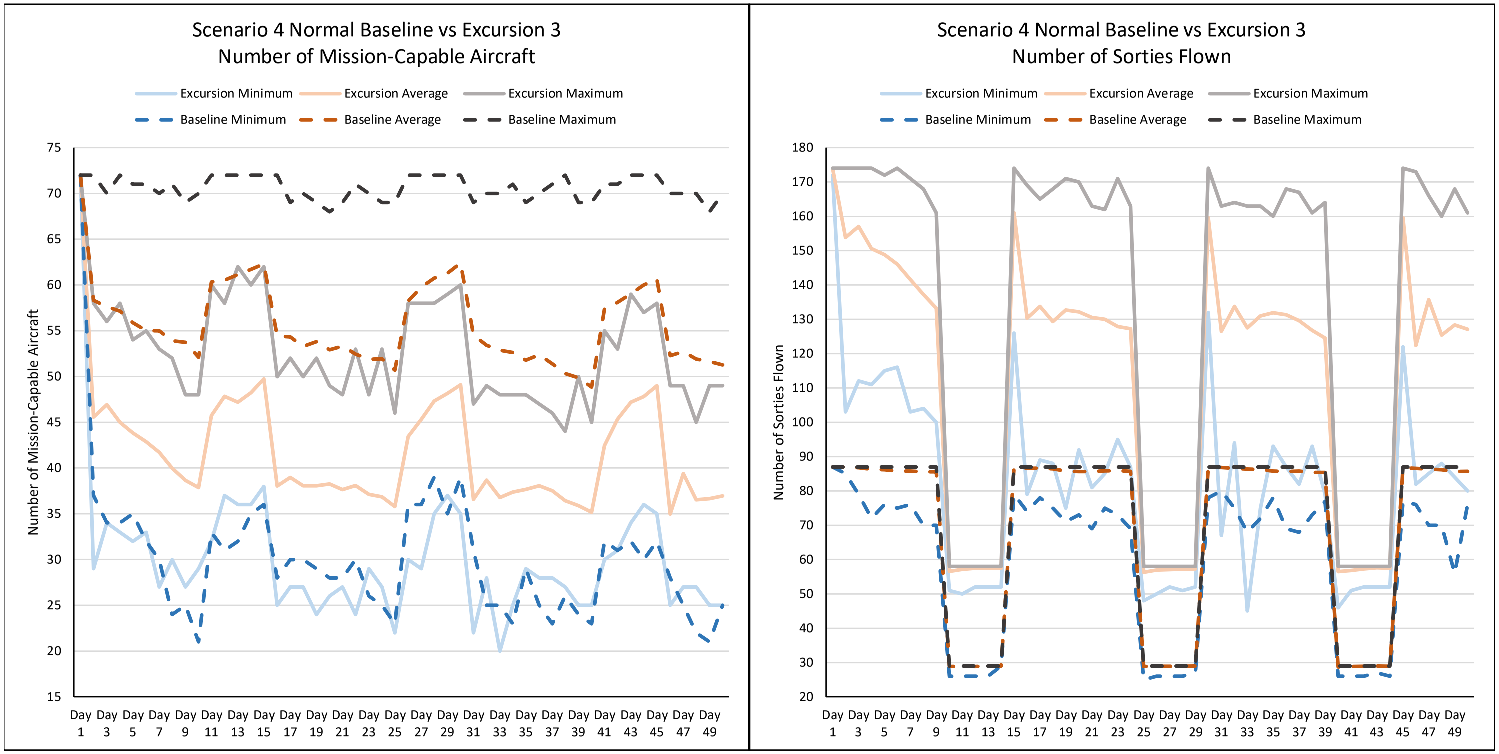


Figure 68. Scenario 4 Normal Baseline versus Excursion 3 Number of MC Aircraft and Sorties Flown

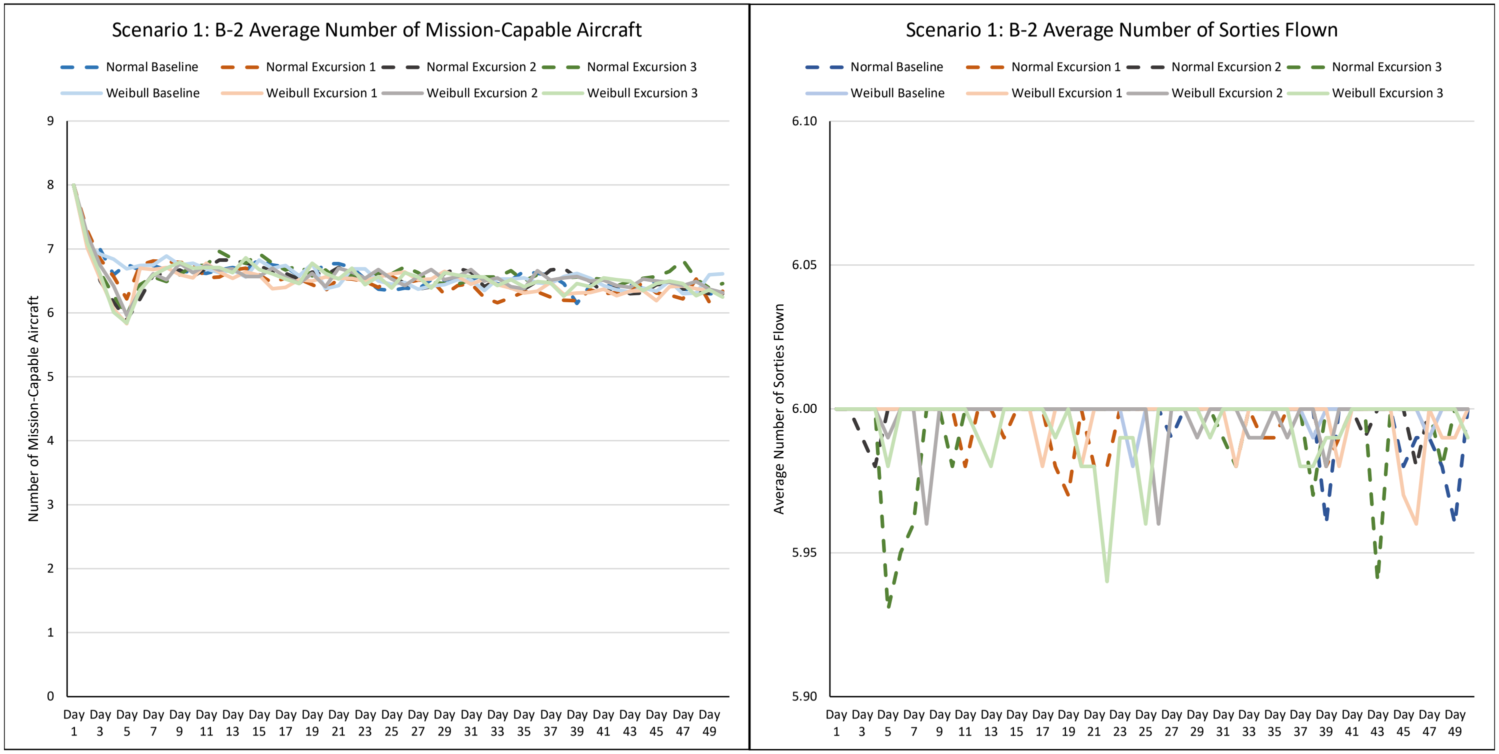


Figure 69. Scenario 1 B-2 Number of MC Aircraft and Sorties Flown

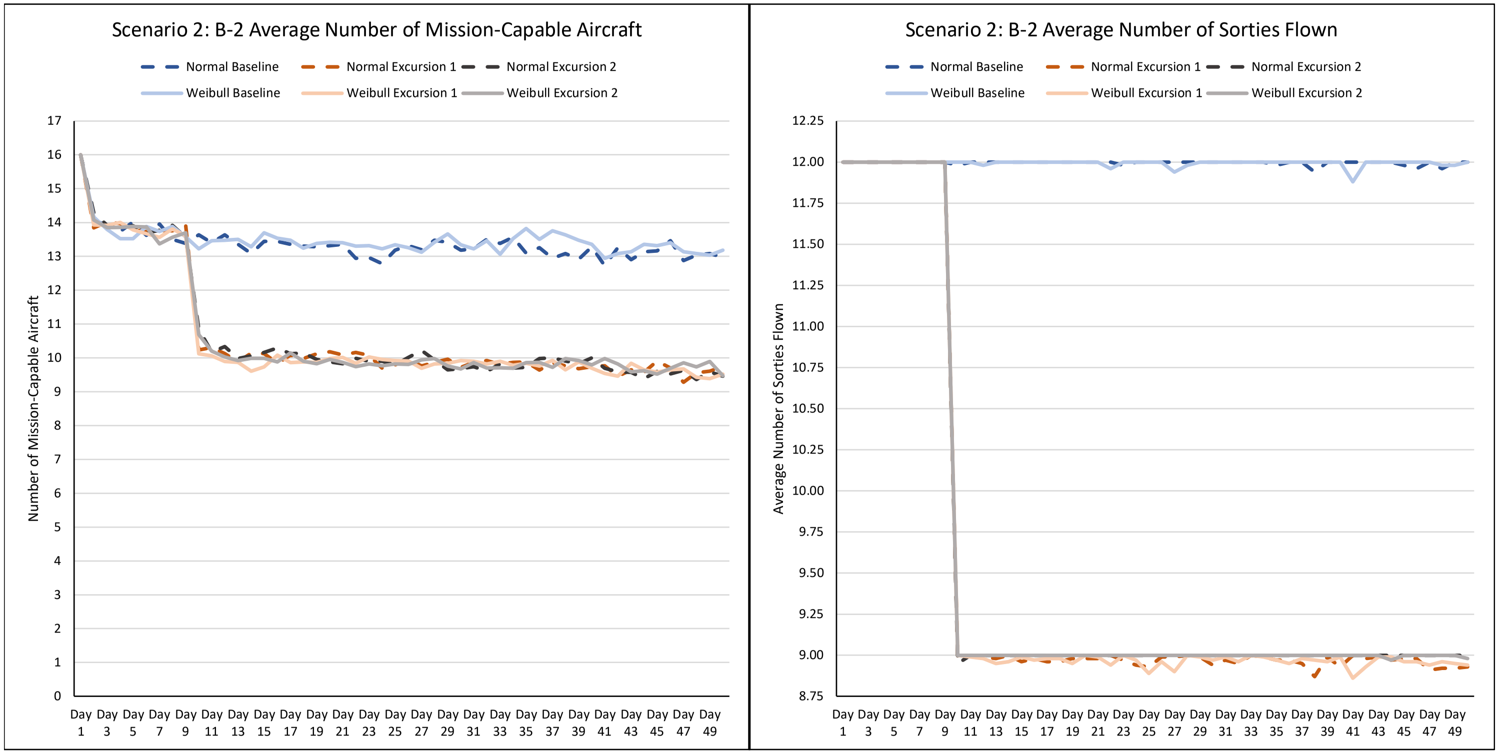


Figure 70. Scenario 2 B-2 Number of MC Aircraft and Sorties Flown

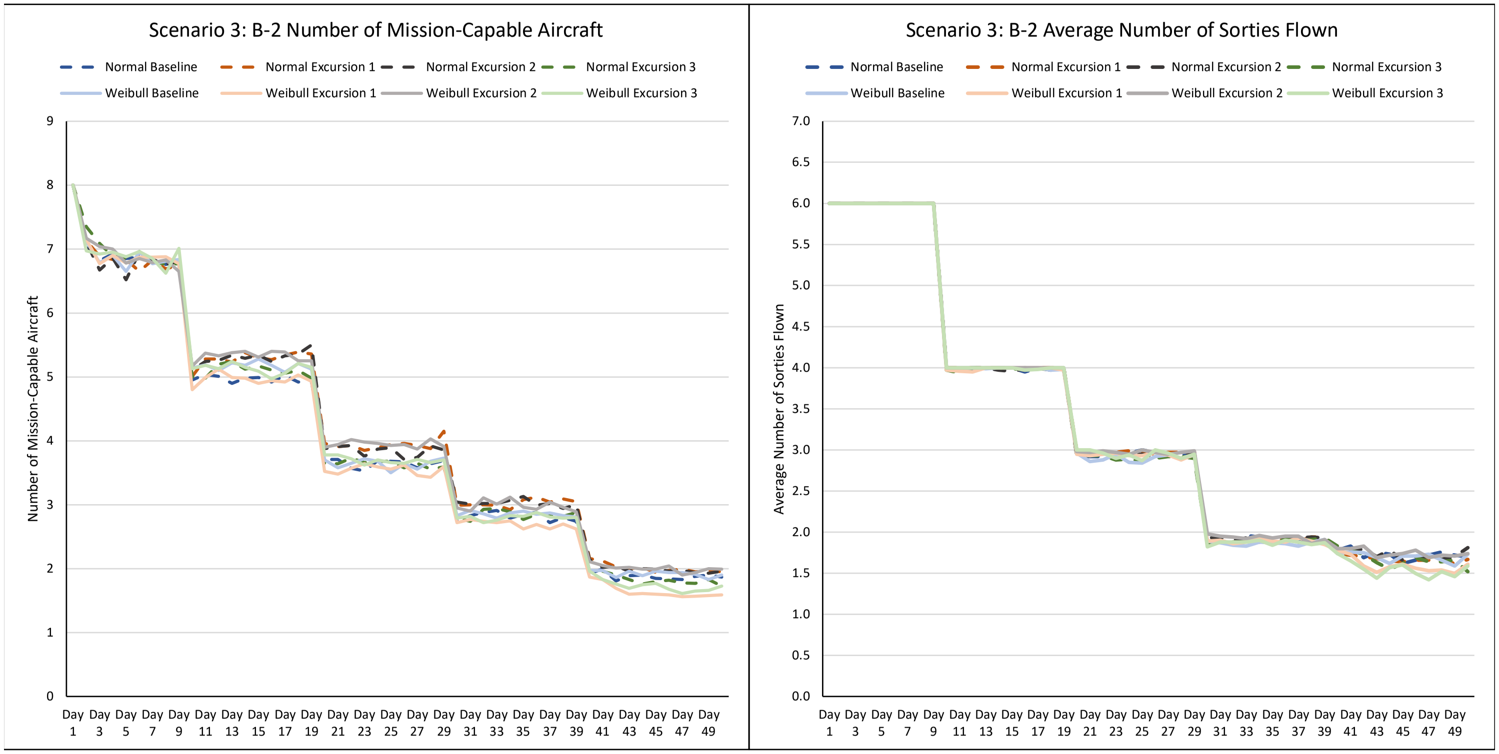


Figure 71. Scenario 3 B-2 Number of MC Aircraft and Sorties Flown

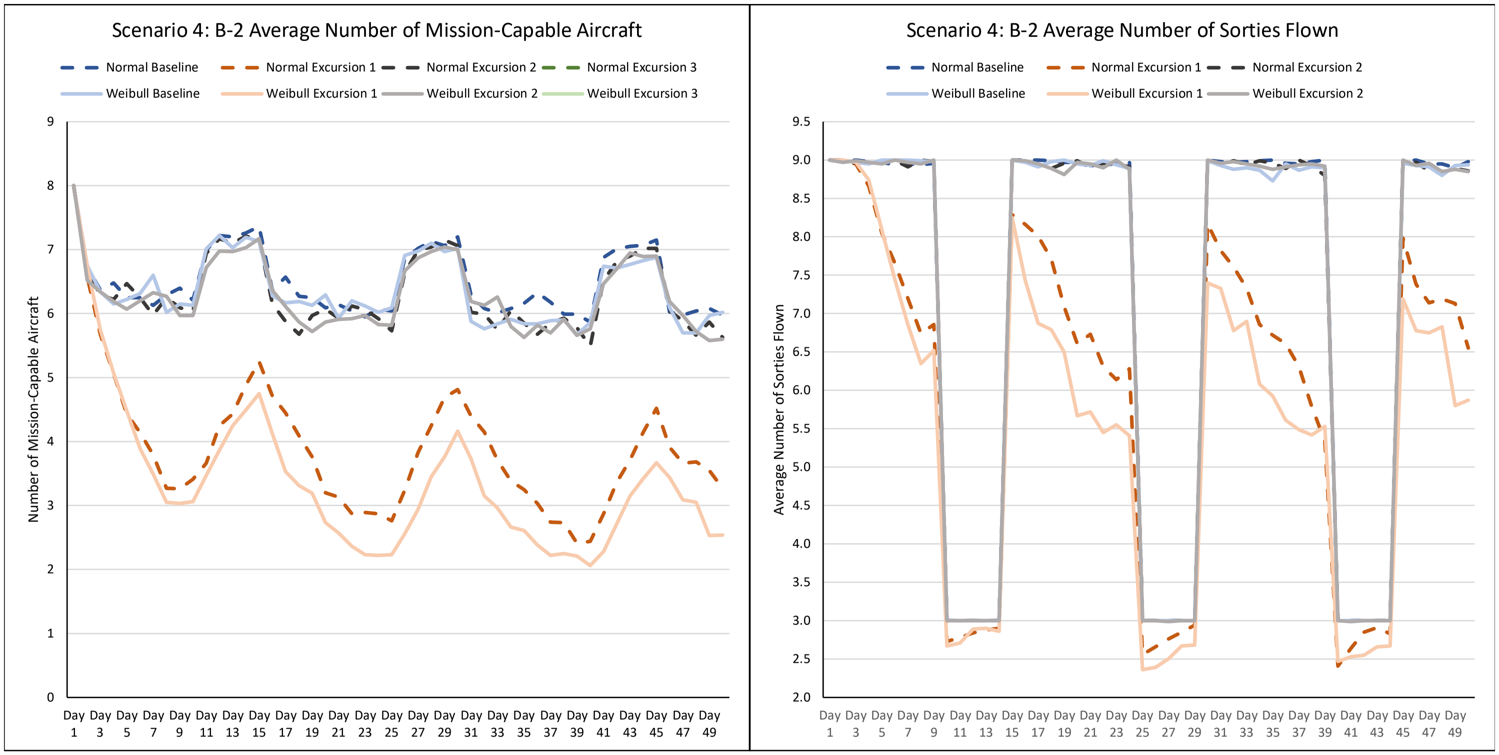


Figure 72. Scenario 4 B-2 Number of MC Aircraft and Sorties Flown

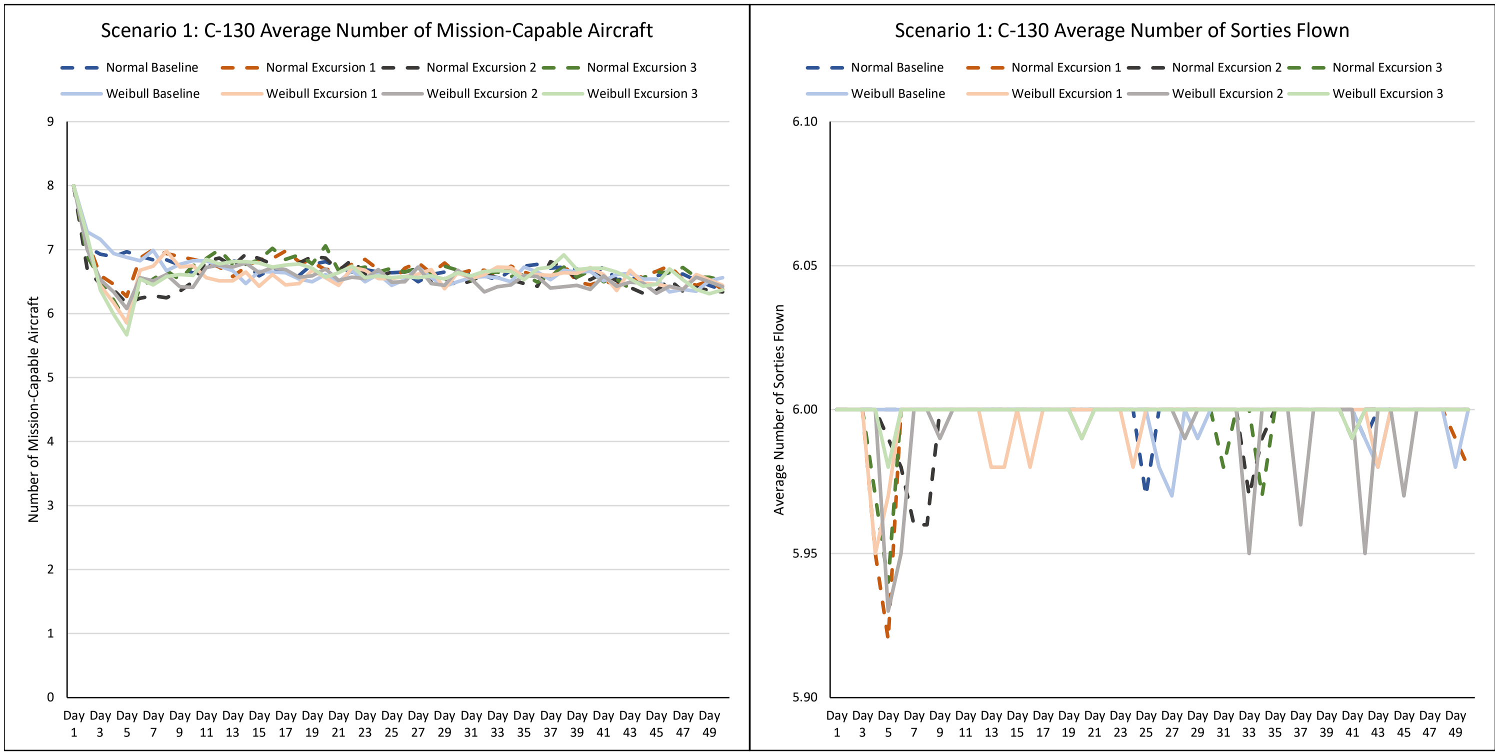


Figure 73. Scenario 1 C-130 Number of MC Aircraft and Sorties Flown

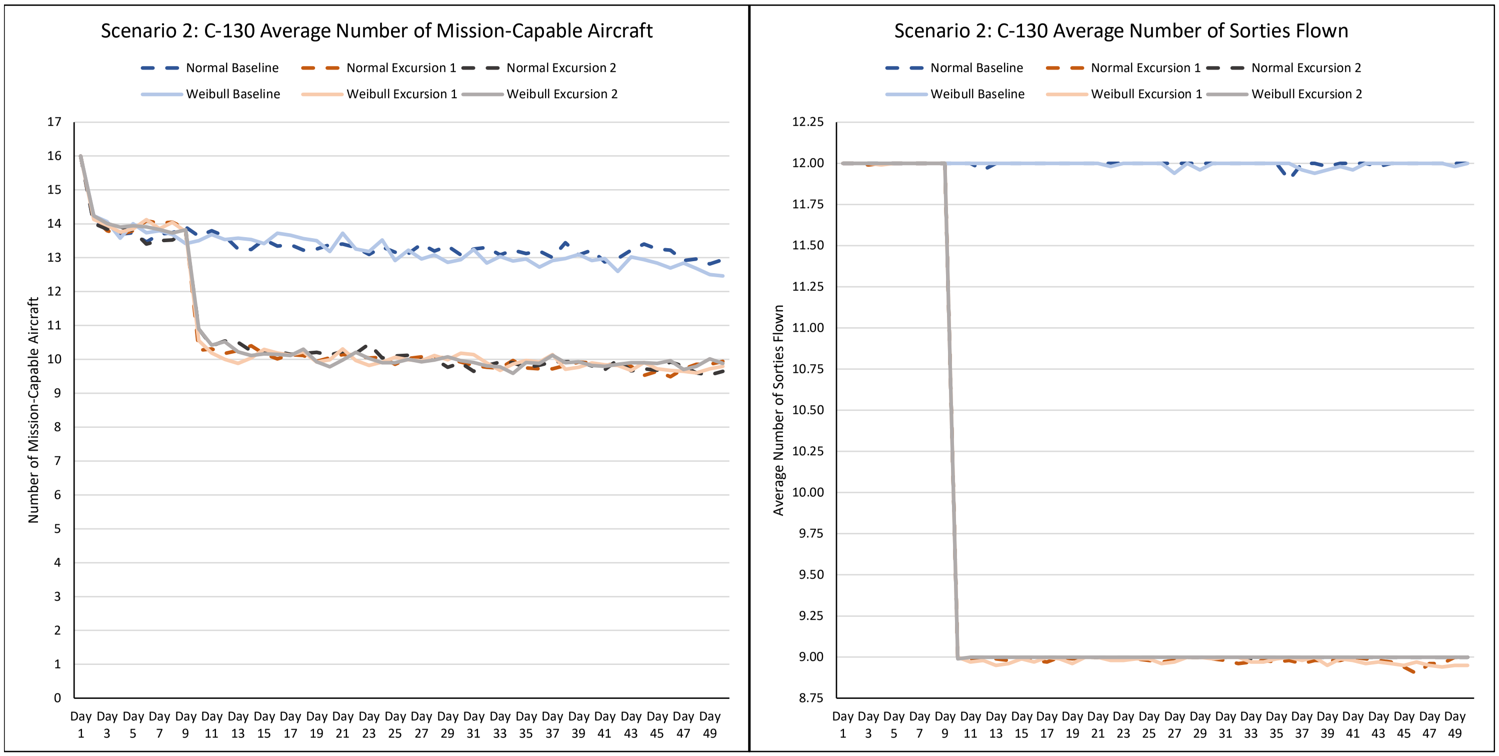


Figure 74. Scenario 2 C-130 Number of MC Aircraft and Sorties Flown

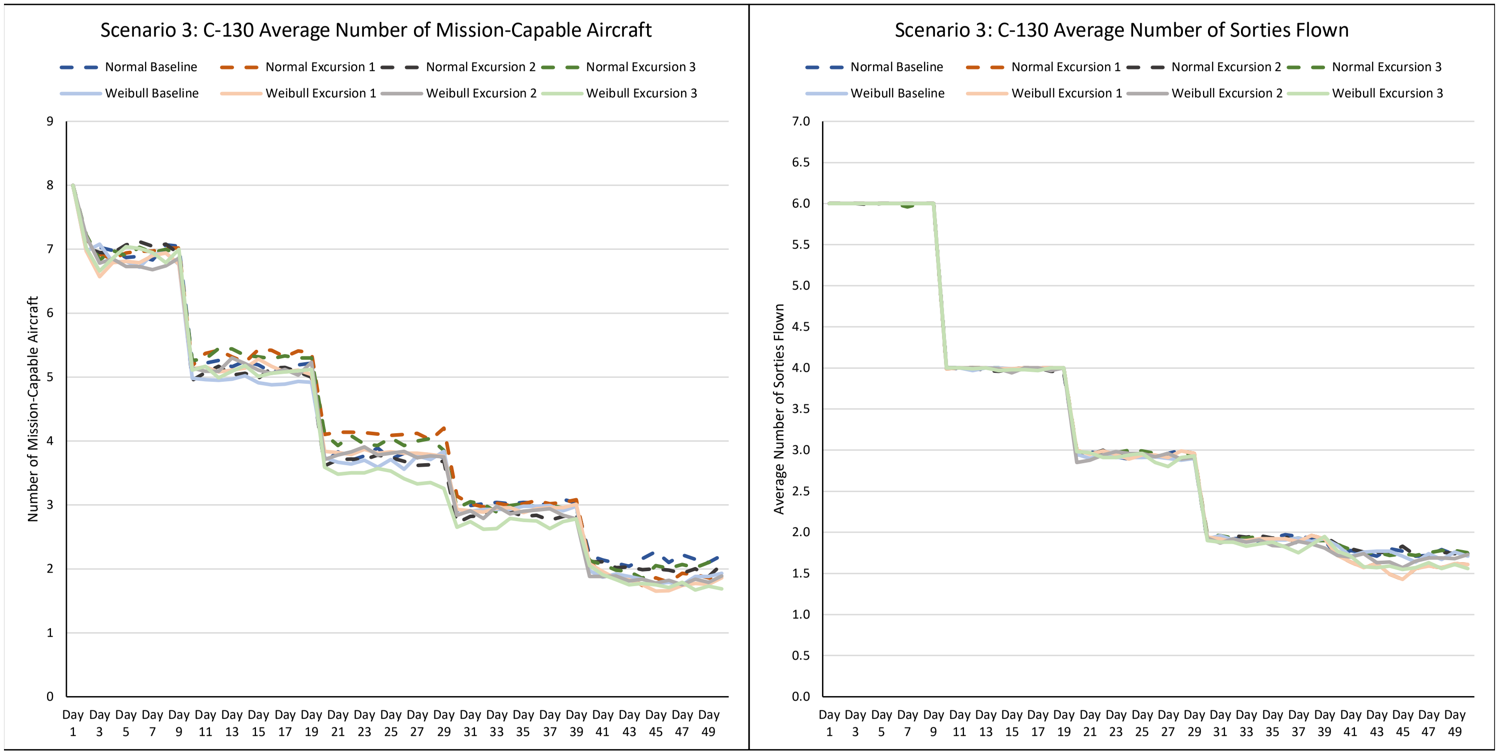


Figure 75. Scenario 3 C-130 Number of MC Aircraft and Sorties Flown

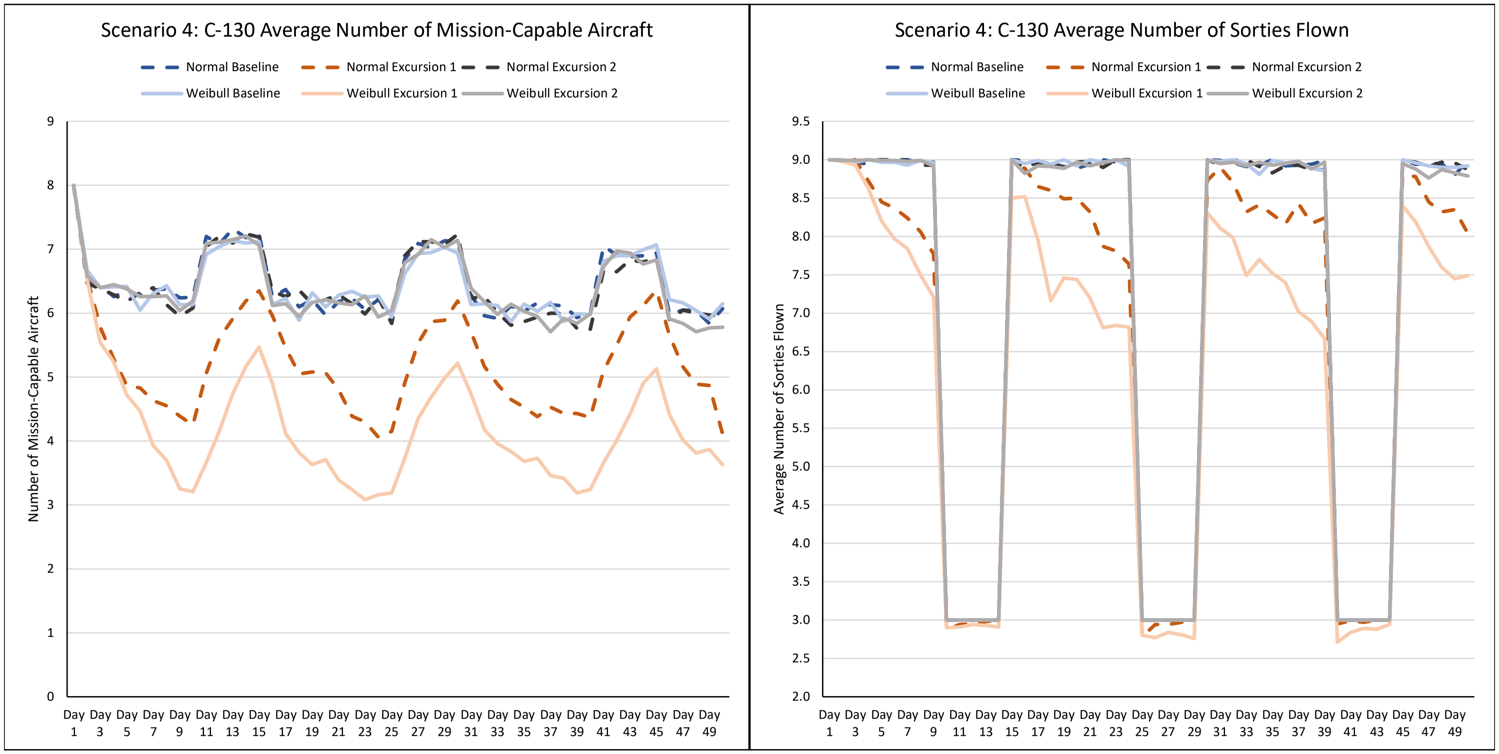


Figure 76. Scenario 4 C-130 Number of MC Aircraft and Sorties Flown

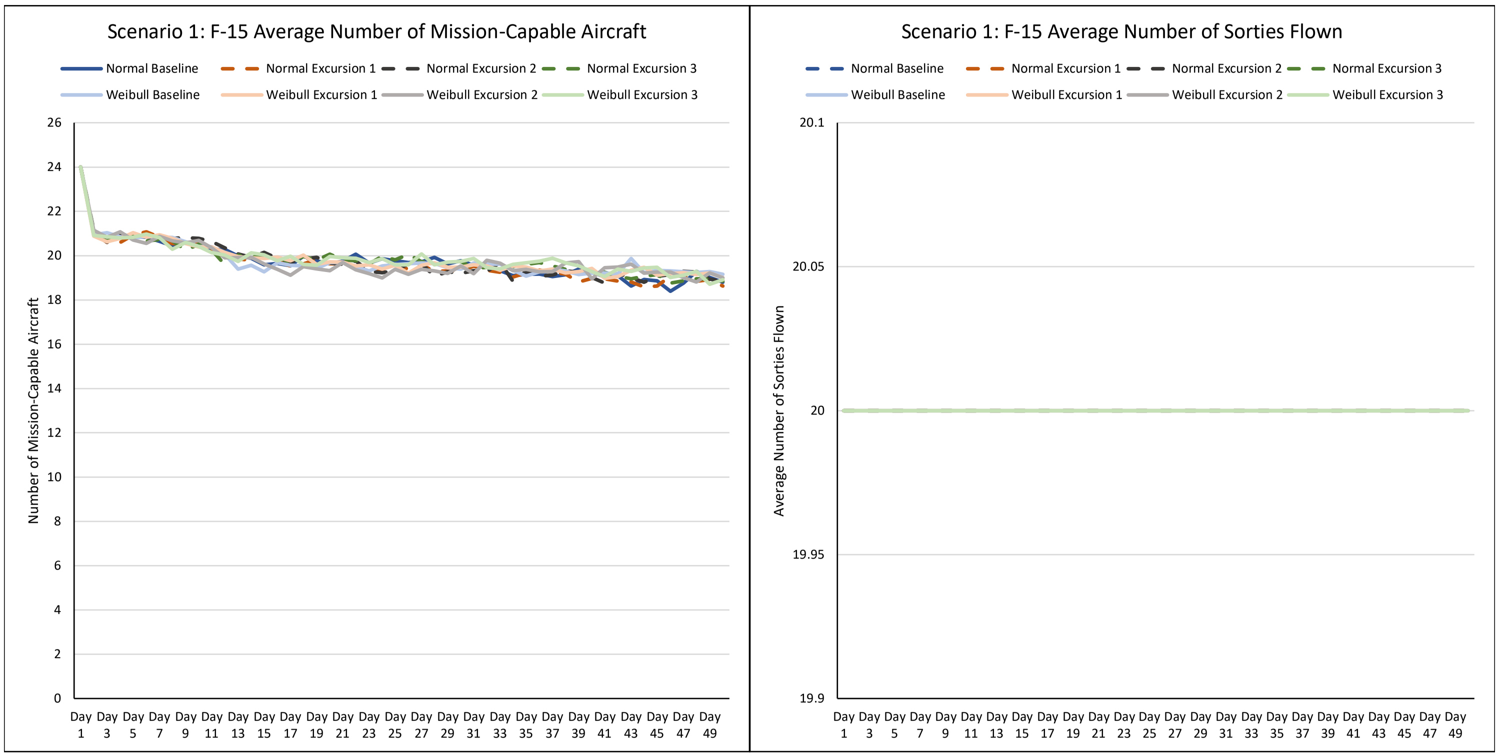


Figure 77. Scenario 1 F-15 Number of MC Aircraft and Sorties Flown

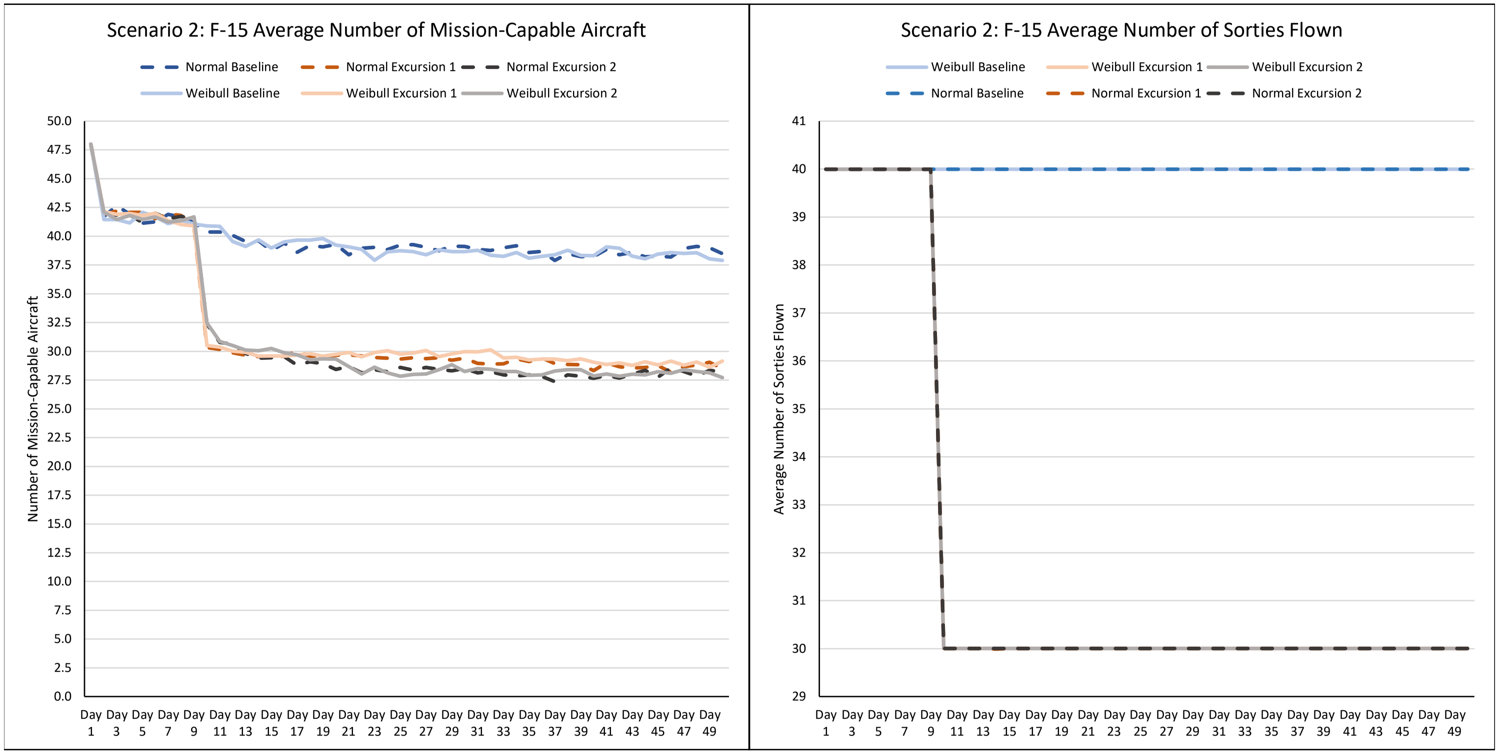


Figure 78. Scenario 2 F-15 Number of MC Aircraft and Sorties Flown

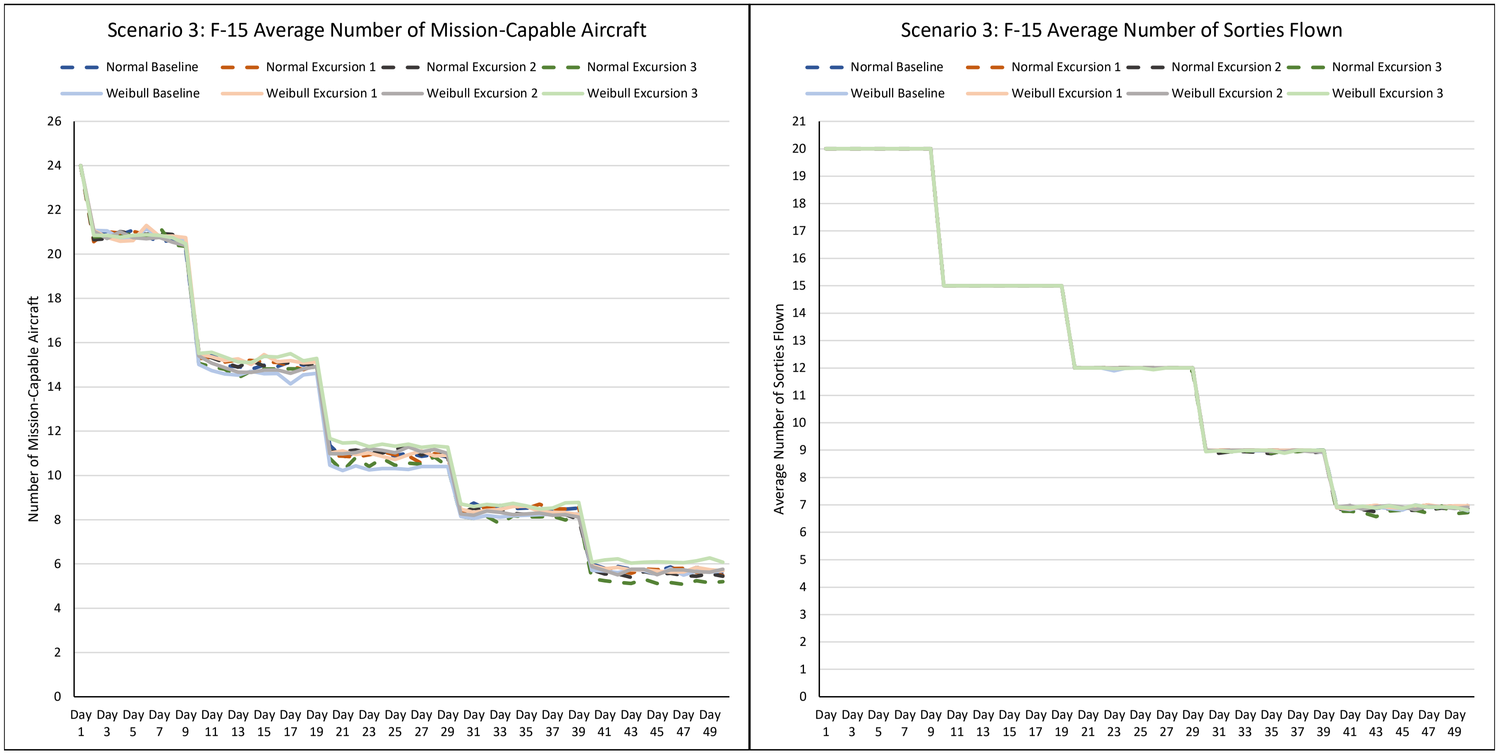


Figure 79. Scenario 3 F-15 Number of MC Aircraft and Sorties Flown

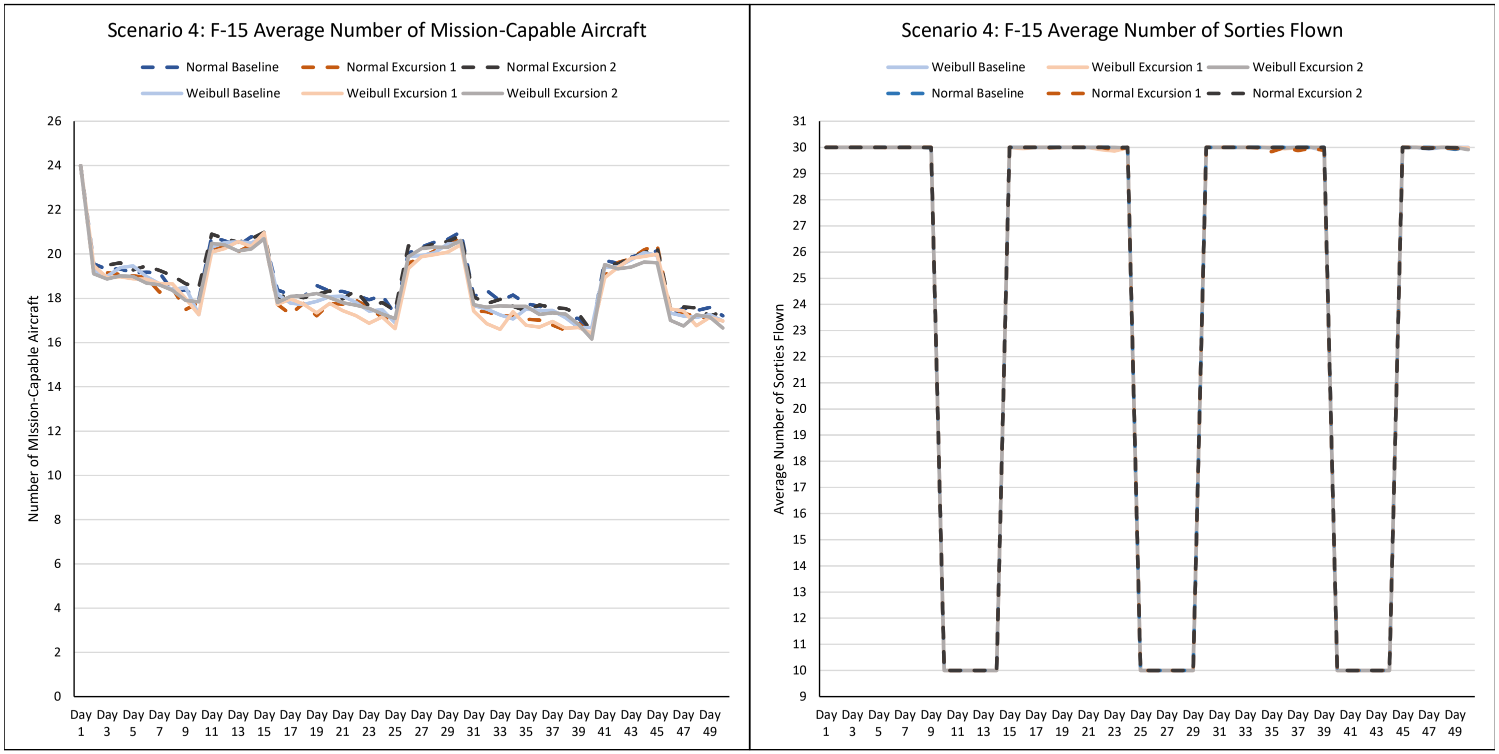


Figure 80. Scenario 4 F-15 Number of MC Aircraft and Sorties Flown

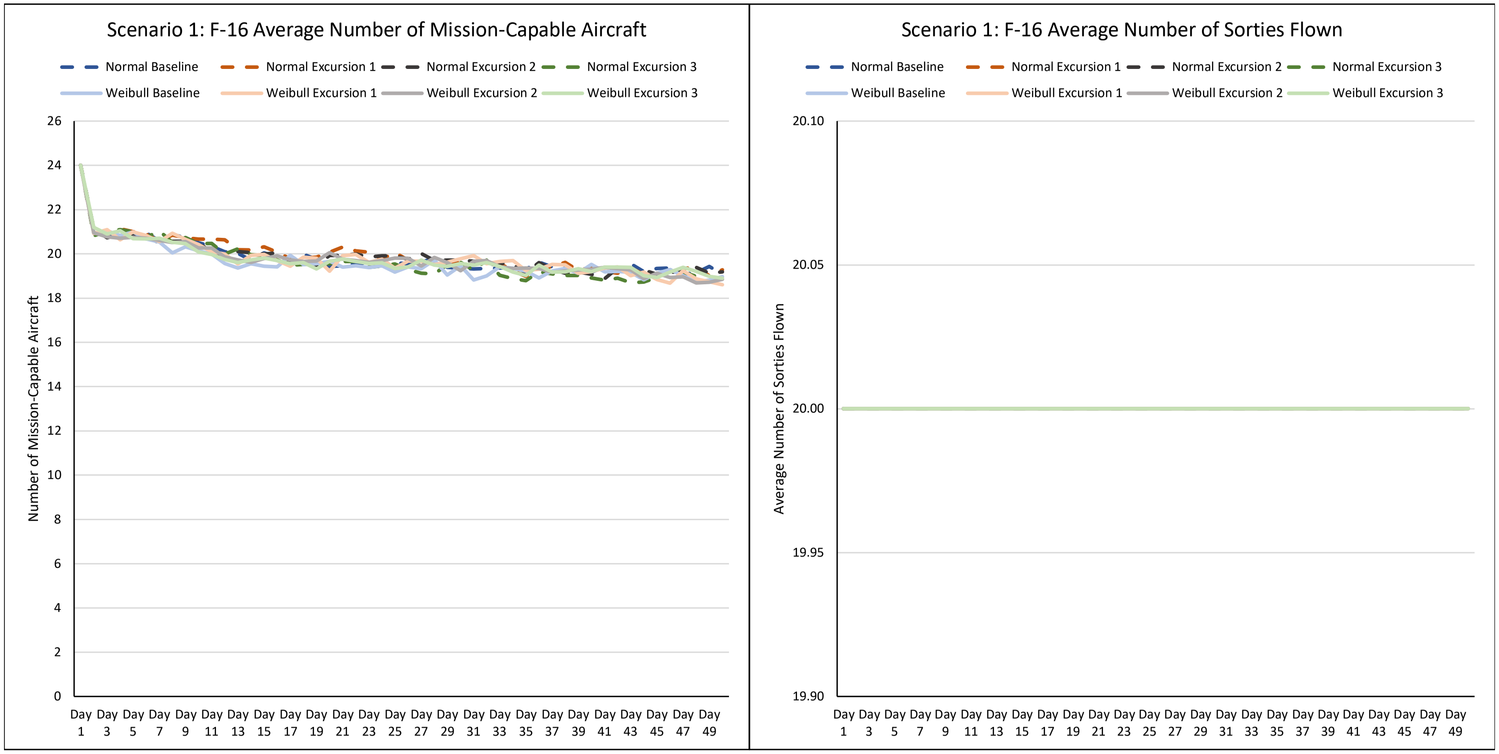


Figure 81. Scenario 1 F-16 Number of MC Aircraft and Sorties Flown

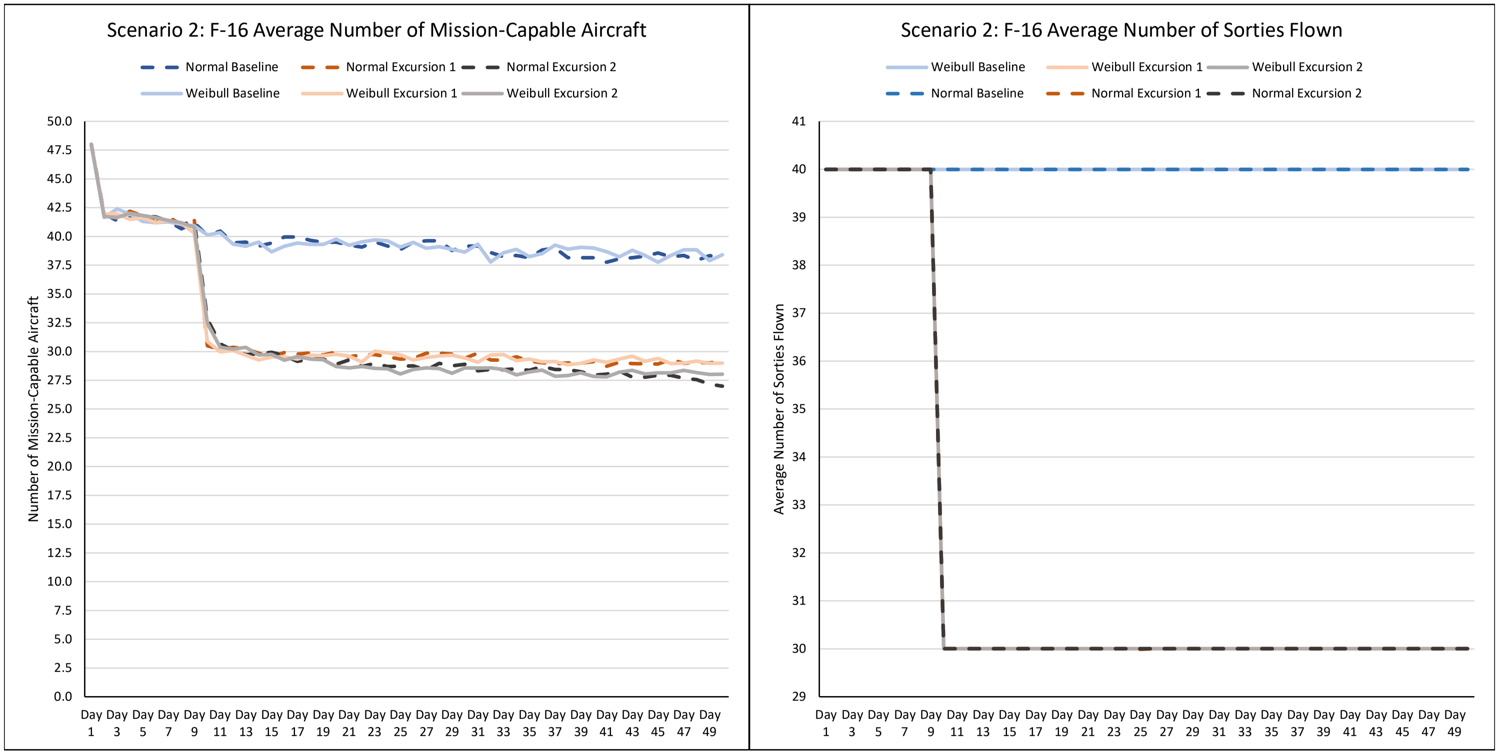


Figure 82. Scenario 2 F-16 Number of MC Aircraft and Sorties Flown

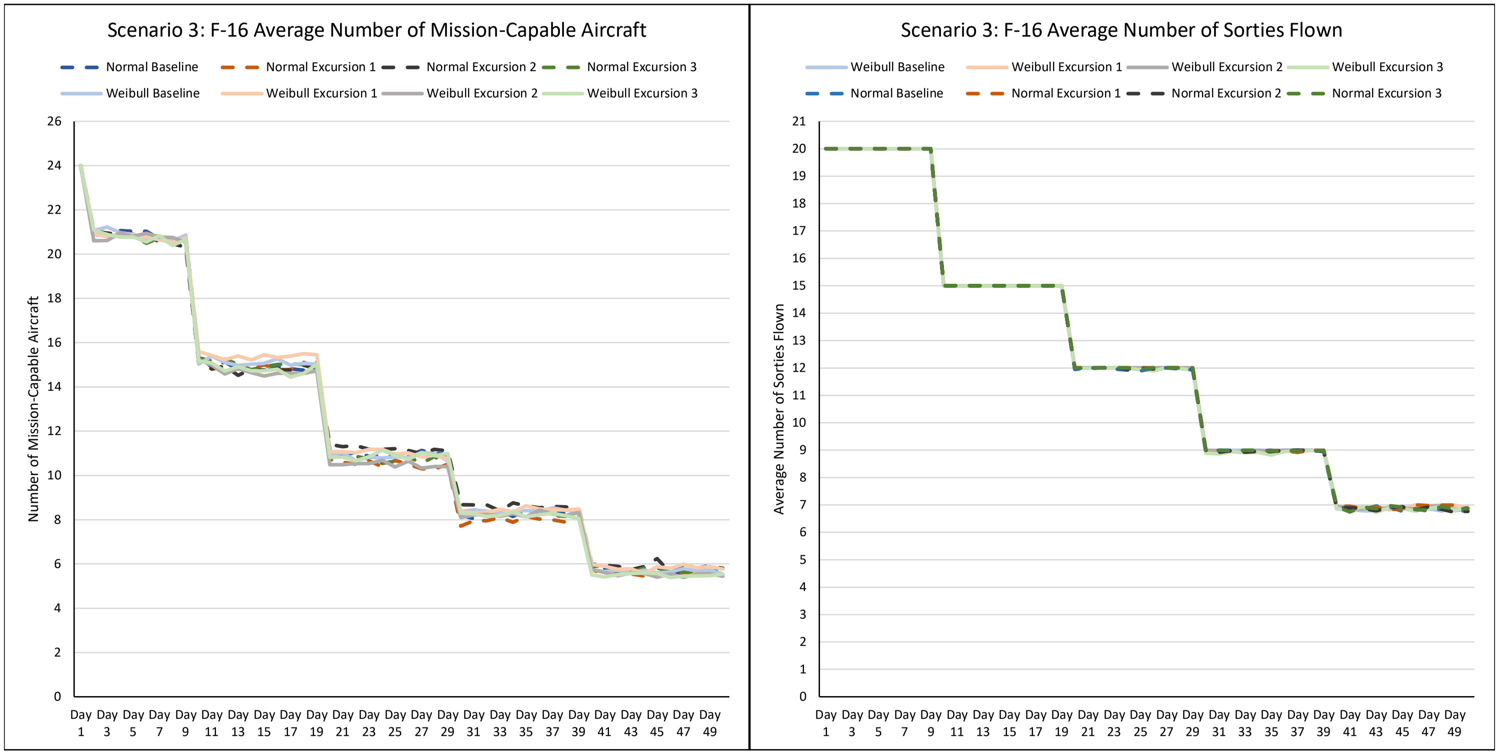


Figure 83. Scenario 3 F-16 Number of MC Aircraft and Sorties Flown

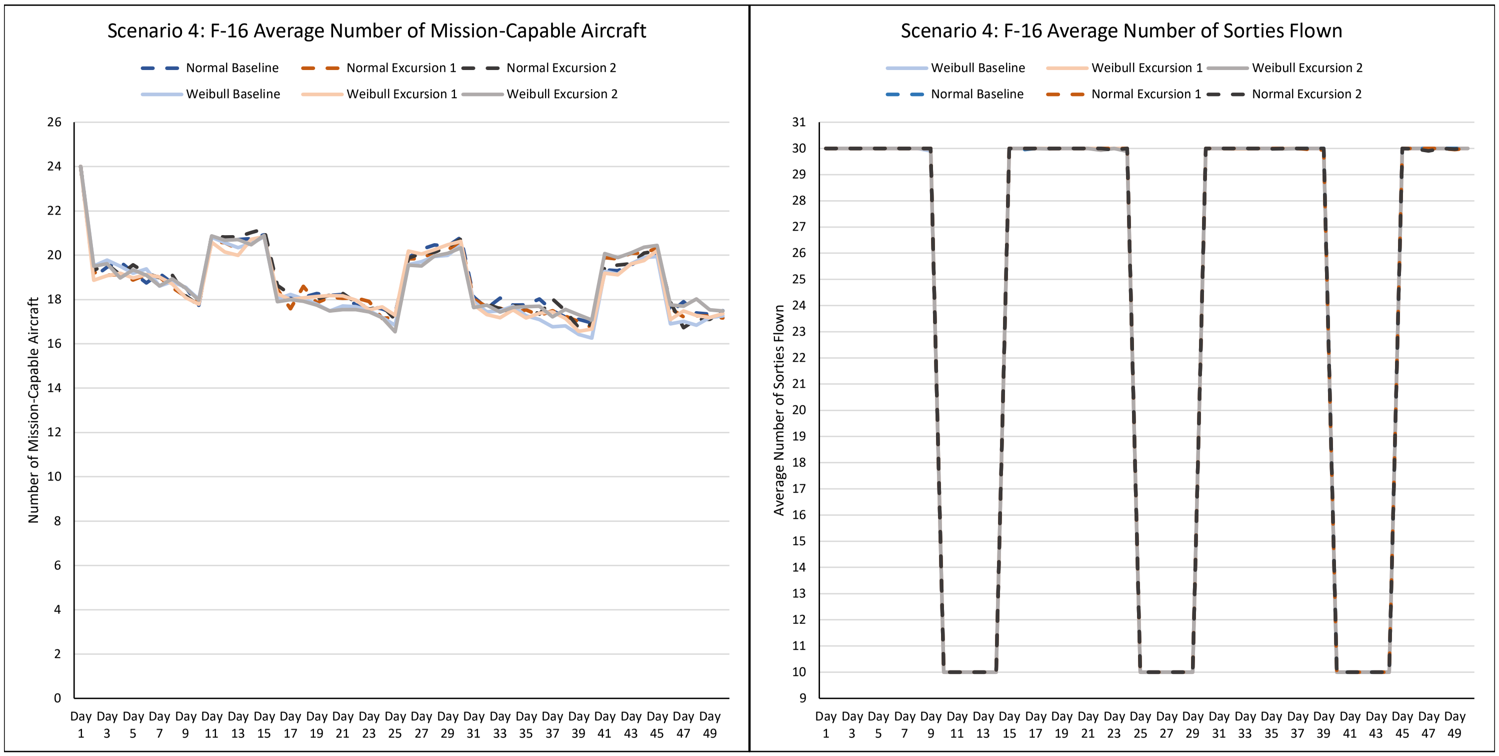


Figure 84. Scenario 4 F-16 Number of MC Aircraft and Sorties Flown

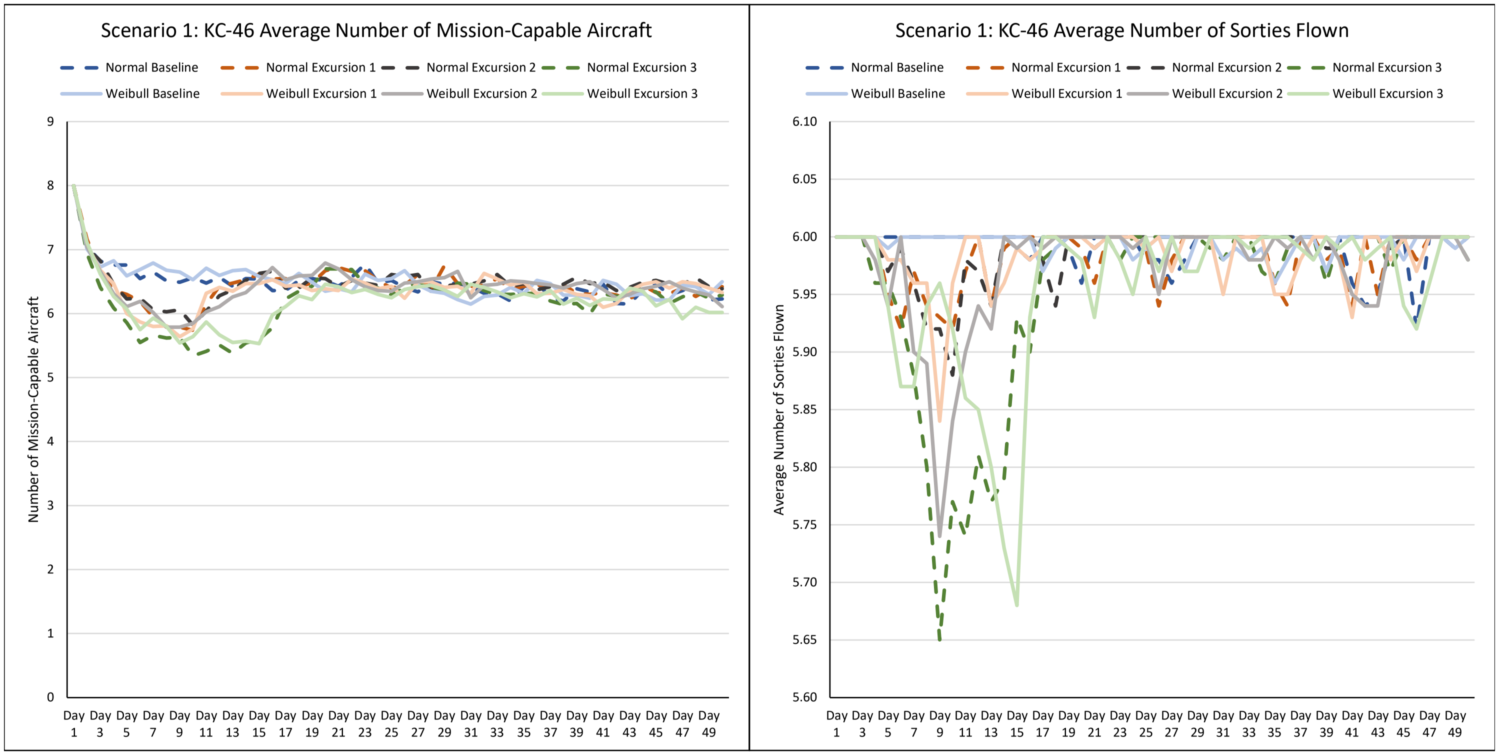


Figure 85. Scenario 1 KC-46 Number of MC Aircraft and Sorties Flown

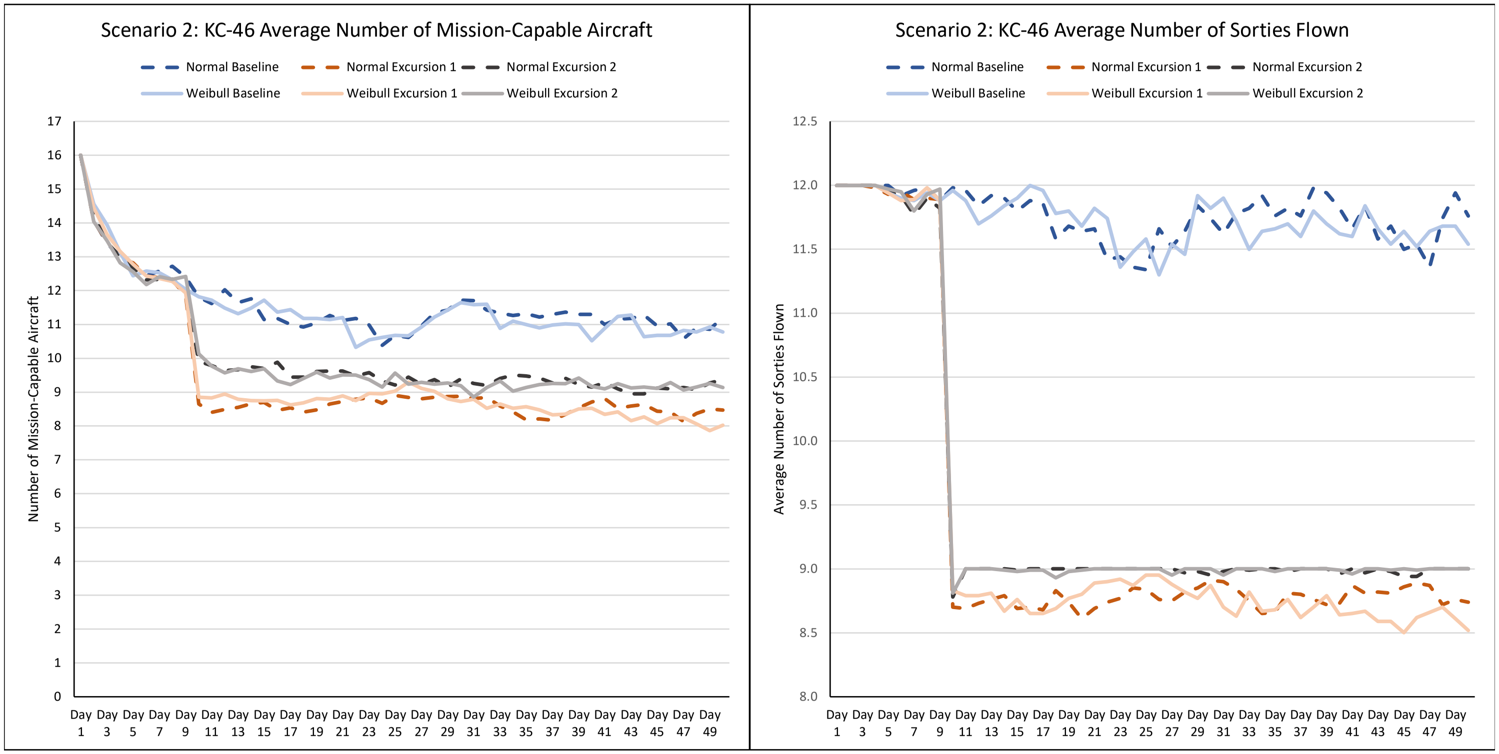


Figure 86. Scenario 2 KC-46 Number of MC Aircraft and Sorties Flown

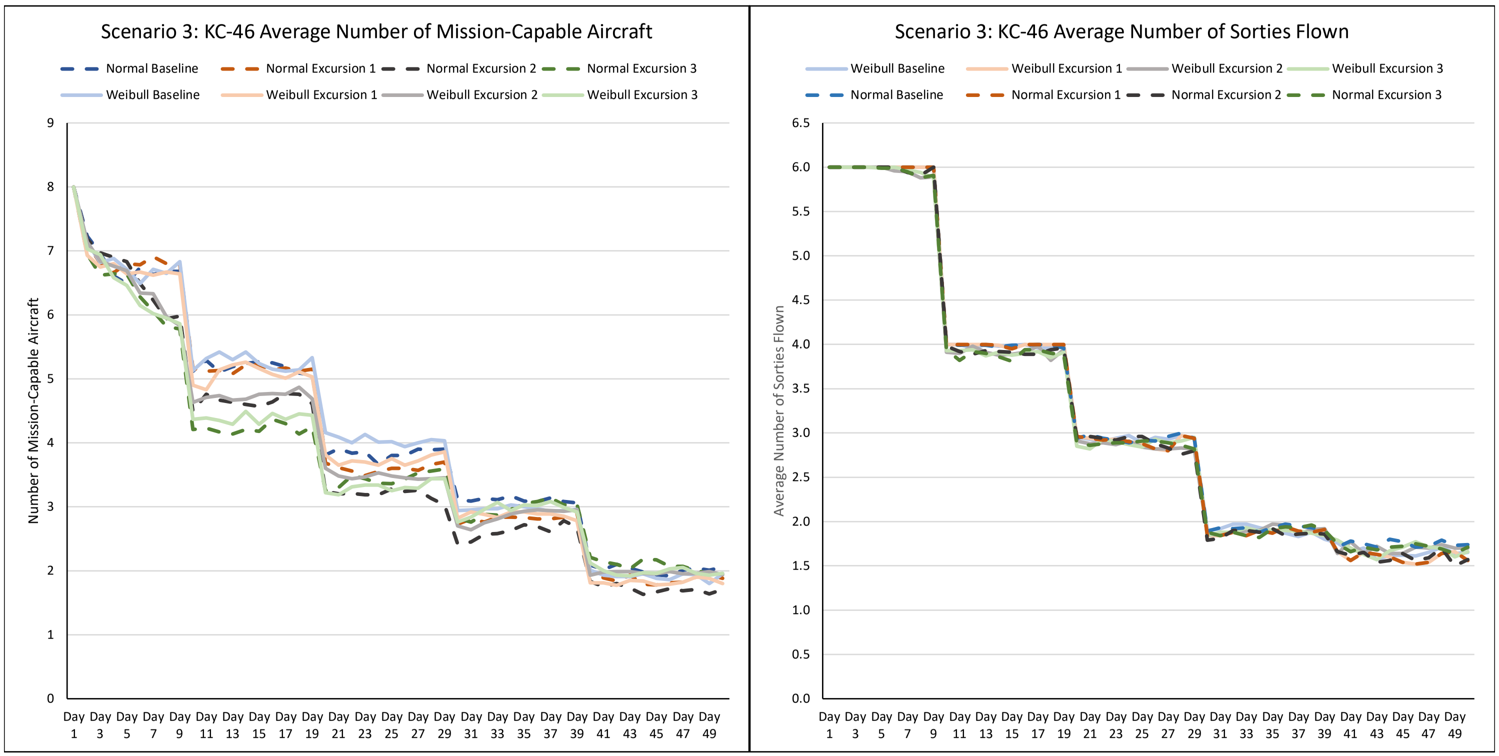


Figure 87. Scenario 3 KC-46 Number of MC Aircraft and Sorties Flown

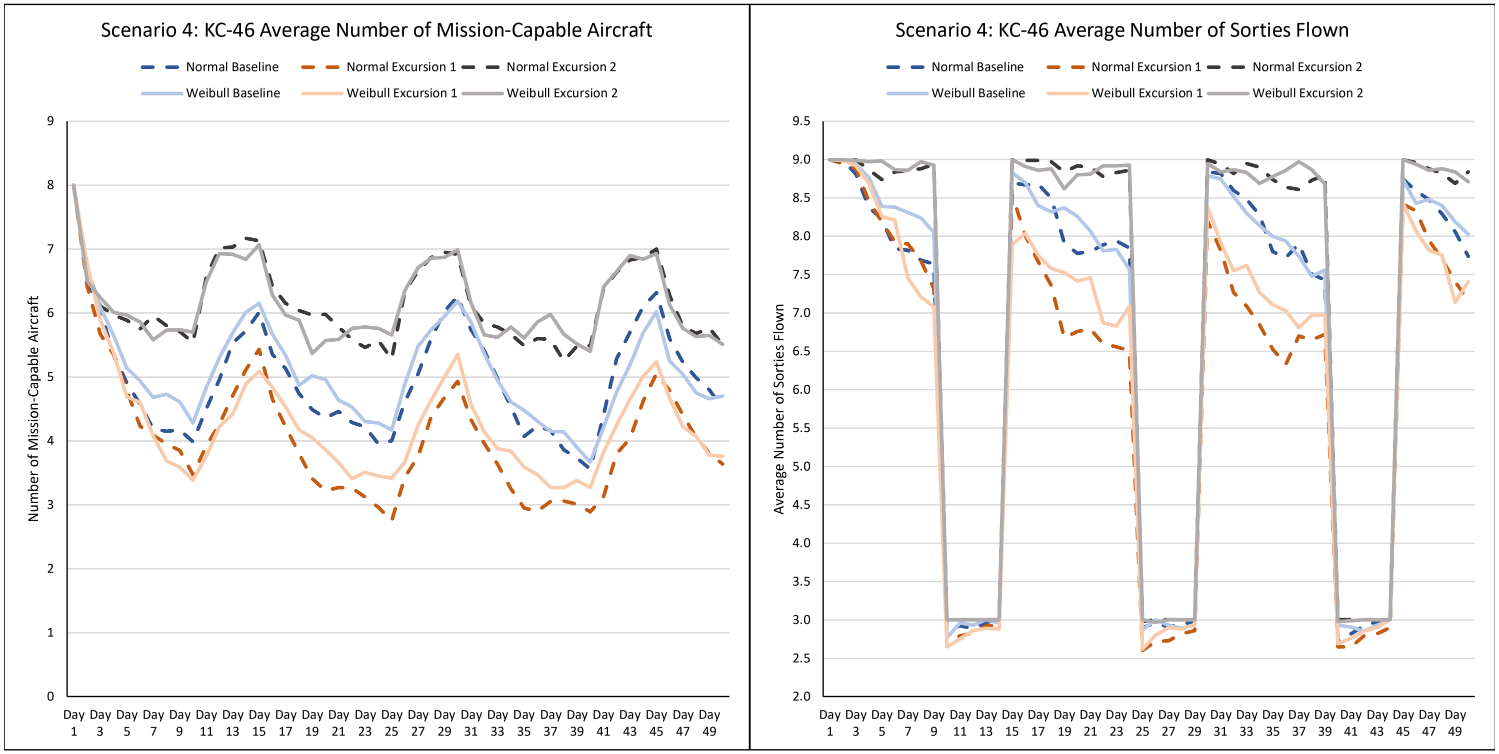


Figure 88. Scenario 4 KC-46 Number of MC Aircraft and Sorties Flown

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14. ABSTRACT

Commanders and wargamers lack tools to quickly determine the number of mission-capable aircraft and number of viable sorties to support wargames and exercises. Less understood is the impact of maintenance personnel on sortie generation. The Expected-Number-of-In-Game-Mission-capable Aircraft (ENIGMA) simulation was developed to calculate the number of MC aircraft and number of sorties flown accounting for the number and type of aircraft, scheduled sorties, mean-time-between-failure, and mean-time-to-repair. ENIGMA is extended by replacing the MTTR input with functions derived from numbers and types of maintenance personnel, providing the impact of maintenance personnel on sortie generation.

15. SUBJECT TERMS

simulation, maintenance manning, sortie generation, mission capable aircraft, mean-time-to-repair

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