Cost and Throughput Analysis for the NASA Ames Arc Jet Modernization Program

GALORATH

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Presented at the 2022 ICEAA Professional Development & Training Workshop: www.iceaaonline.com/pit2022

Arc Jet Modernization Objectives

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- Extend lifetime of test capability by 20+ years
- Reduce annual operating (O&M) costs by 25% (fixed/indirect costs)
- Downtime local cost avoidance RO.

COST AVOIDANCE

PRIMARY MOTIVATION IS NOT LABOR COST

Upgrades to facilities will likely reduce labor costs to operate, however that is not the biggest motivation

MISSION COST AVOIDANCE

Complex planetary missions and crewed systems that cost billions of dollars each is a bigger driver

The inability to test when required can be expensive!

SCHEDULE SLIPS

Schedule slips lead to cost growth – a standing army of contractors must be paid over a longer period of time

BOTTOM LINE

We have conducted simulation studies that show that the mission cost avoidance from being able to test when needed can save hundreds of millions of dollars over 20 years

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Arc Jet Complex Facilities

Aerodynamic Heating Facility (AHF)

Designed to simulate the "heating rates of Earth or planetary hypersonic entry to enable the selection, validation, and qualification of thermal protection systems (TPS) and materials."

Turbulent Flow Duct (TFD)

Provides supersonic turbulent flow over flat services.

Interaction Heating Facility (IHF)

Tests the thermal impact resultant from "the interaction of an energetic flow field during a hypersonic entry into a planetary atmosphere."

Panel Test Facility (PTF)

Tests "spacecraft heat shield material samples in a high enthalpy, high shear boundary layer flow field"

The Arc Jets

There are seven test bays distributed among the four arc jets, which are devices in which "gases are heated and expanded to very high temperatures and supersonic/hypersonic speeds by a continuous electrical arc between two sets of electrodes."

Supporting Facilities

The Arc Jets are supported by large and complex common facilities and equipment

Steam Vacuum System (SVS)

High-volume, 5-stage steam ejector vacuum-pumping system that in combination with the power supply enables the facility to match high-altitude atmospheric flight conditions with test articles of relatively large size.

De-ionized (DI) Water System

The DI water tank is located at ground level within the footprint of the SVS and much of the deionized water supply and return piping is in the basements

Other

- Two direct current power supplies
- High pressure gas systems
- Controls

Within these facilities are abandoned structures (e.g., supporting I-beams and pipes) that further complicate the modernization efforts of interdisciplinary facilities. This is one of the major cost drivers in the investment and throughput analysis of each alternative.

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Implementation Cost Estimate Methodology

Primary Estimating Methodology

Building Blocks

Project-Specific Adjustments

NASA Ames Overhead: Provided by NASA Ames to capture the total cost of the program to NASA.

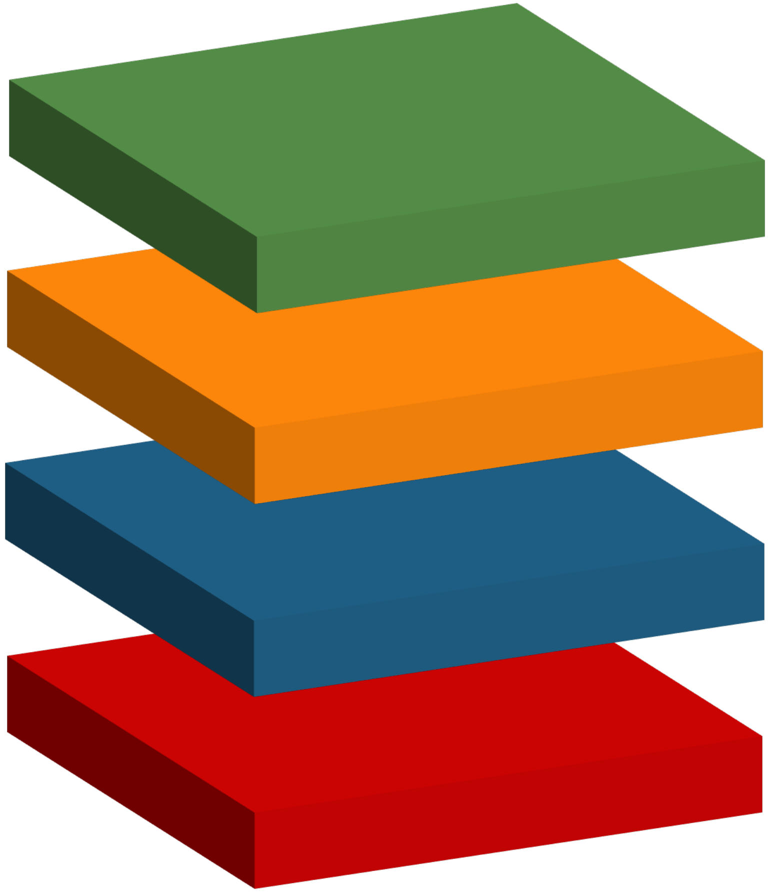
Seismic Activity: Independent research

Source Costs

RS Means: Database of current construction cost estimates, including materials, labor, transportation, storage, and salvage.

PAX Newsletter: Table of Army Facility types and their construction cost per square foot

UFC 3-730-01: Guidance unit costs using Marshall and Swift, RS Means, and PAX Newsletters.



Adjustments

UFC: Historical Factor, Design Contingency, Construction Contingency, Planning and Design (P&D), and Supervision, Inspection, and Overhead (SIOH)

RS Means: Labor Productivity Adjustment

PAX Newsletter: Area Cost Factor (ACF)

Guidance

Unified Facilities Criteria (UFC) informs the structure and methodology of the estimate. There are stringent congressional notification requirements for construction, and it is prescribed by Military Standard 3007 and provides guidance for cost estimating military construction projects.

Estimate Adjustment Factors

Title	Description	Source	Value
Area Cost Factor	The ACF evaluates a market basket of Labor, Material, and Equipment (LME) and normalizes. Then, the LME is modified by 7 Matrix factors that cover local conditions affecting construction costs. These Matrix factors include weather, seismic, climatic (frost zone, wind load), labor availability, contractor overhead and profit, logistics and mobilization, and local labor productivity versus the US standard	PAX Newsletter 3.2.1	1.20
Historical Factor	The Historical Factor (HF) is an adjustment to account for increased costs for replacement of historical facilities or for construction in a historic district. If the facility does not qualify as "historical," this factor is 1.	UFC 3-701-01 DoD Facilities Pricing Guide, with Change 8 (3 Feb 2021)	1.00
Labor Productivity Adjustment	Loss productivity caused by congested work area. Default is 3 hours of non-productivity per week or approximately 97%. Additionally, RSMeans data from Gordian shows that infectious disease/COVID precautions can reduce the amount of available work time by up to 10%, thereby increasing labor costs on job sites, especially those with restrictive COVID requirements. Construction work tasks that are associated with high exposure risk levels and publicly funded construction projects will require the most COVID precautions.	UFC 3-730-01 Programming Cost Estimates for Military Construction, With Change 2 RS Means data from Gordian	90.00%
Design Contingency	Design contingency allowance may be included based on the lack of maturity of design data. The design contingency (DC) allowance is to cover component items that cannot be analyzed or evaluated at the time the facility cost estimate is prepared; however, such items are susceptible to cost evaluation as engineering and design progresses. The DC depends on the reliability and refinement of the data on which the estimate is based; it therefore diminishes as design progresses from the pre-design stage through the design completion stage. Although it lessens at each successive design stage, the initial magnitude of the DC at the pre-design stage depends on the technical complexity of the project for which the facility cost estimate is being prepared. The level of technical complexity must first be established as a prerequisite for determining the magnitude of the DC. Technical complexity levels and design contingency factors are listed in the tab Supporting Data - Factors.	UFC 3-701-01 DoD Facilities Pricing Guide, with Change 2 (21 May 2020)	Component Dependent

Estimate Adjustment Factors

Title	Description	Source	Value
Construction Contingency	Each project cost estimate should include a separate item as a reserve for construction contingencies to cover construction requirements, which cannot be foreseen before the contract is awarded. The contingency reserve is for some adverse or unexpected condition not susceptible to predetermination from the data at hand during engineering and design; it must be included in the project cost estimate. This reserve is usually for latent difficulties, such as unforeseeable relocations; unforeseeable foundation conditions; encountering utility lines in unforeseeable locations; or other unforeseen problems beyond interpretation at the time of contract award. The contingency reserve is not an allowance for omissions of work items which are known to be required, but for which quality or quantity has not yet been determined by specific design. Reasonable allowances for all foreseeable requirements should be made in the estimate or shown as an allowance for cost adjustment. Application for construction contingency reserves will be in accordance cognizant design agency guidance. The construction contingency reserve for military construction programs and family housing new or replacement construction will normally be 5 percent of the total estimated contract cost.	UFC 3-701-01 DoD Facilities Pricing Guide, with Change 2 (21 May 2020)	5.00%
Planning and Design	Planning and Design (PD) is a factor to account for the planning and design of a facility; the current value of this factor is 1.09 for all but medical facilities, and 1.13 for medical facilities.	UFC 3-701-01 DoD Facilities Pricing Guide, with Change 8 (3 Feb 2021)	9.00%
Supervision, Inspection, and Overhead	Supervision, Inspection, and Overhead (SIOH) is the factor to account for the supervision, inspection, and overhead activities associated with the management of a construction project. The current value of the factor is 1.057 for facilities in the (CONUS), and 1.065 (USACE) or 1.062 (NAVFAC) for facilities in the (OCONUS).	UFC 3-701-01 DoD Facilities Pricing Guide, with Change 8 (3 Feb 2021)	5.70%
NASA OH	PM Shop, PMSEMA, etc.	NASA Ames	21%

Seismic Adjustment

Above the seismic calculation included in the ACF

The cost premium for earthquake-resistant construction is of great interest in regions that have significant seismic hazard, but have not suffered serious damage from earthquakes in the memories of people now living. The middle Mississippi River Valley was struck by very large earthquakes in 1811 and 1812, and scientific study has found evidence of multiple large earthquakes prior to that. This history indicates that the risk for loss of human life due to earthquake hazard in the region is high. This inference is confirmed by hazard assessment information based on expert consensus studies conducted by leading seismologists who are engaged with the U.S. Geological Survey. Based on risk to life-safety, the hazard is very similar to coastal California, but there have been essentially no damaging earthquakes to remind the populace of the hazard. This understandably leads to questions about the value (cost) of including earthquake-resistant construction requirements in the local building codes.

Cost Analyses and Benefit Studies for Earthquake-Resistant Construction in Memphis, TN

https://www.atcouncil.org/files/NIST%20GCR%2014-917-26_CostAnalysesandBenefitStudiesforEarthquake-ResistantConstructioninMemphisTennessee.pdf

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For an office building, increase is equal to 19.6% for the structure

Estimating Methodologies

Assessment of Application in NASA Arc Jet Complex Modernization

Analogy

- Arc Jet Facilities are unique even within NASA
- NASA facilities data availability is limited
- Any applicable historical data point, usually at a component level, was used

Vendor Quotes

- Very difficult to acquire given the sensitivity of the facility
- Validity time periods extremely short
- Used for some less specialized systems (e.g., DI Water piping)

Engineering Build-Ups

- Time-consuming
- Imprecise in early trade analyses
- Improved greatly after quantification of execution complexity

Parametric

- Developed many Cost Estimating Relationships (CERs) to adjust for size
- Standard Size Adjustments used when able, but also used proprietary SEER-MFG to develop tank estimate

Schedule Analysis

Schedules for each phase based on the Saturn S-IC Static Test Facility data. Each phase is a period of deconstruction and construction to incrementally build-up the new facility.

Escalation

Engineering News Record (ENR)data is used to calculate inflation indices

Subscription to ENR is expensive, and Galorath was lucky to have Glenn Butts at Kennedy Space Center share the historical data.

He has also done extensive research to capture the effects of the market on the construction industry prices. Even with this responsible estimating, he has seen several recent bid-busters. Galorath has also noted the short validity time of quotes (rarely more than one month, sometimes as short as a week, that are 1.5-2x as expensive as what is seen in RS Means.

CONSTRUCTION ECONOMICS

ENR's 20-city average cost indexes, wages and material prices. Historical data and details for ENR's 20 cities can be found at ENR.com/economics

Construction Cost Index — ANNUAL INFLATION RATE — +8.4% SEPT. 2021

1913=100	INDEX VALUE	MONTH	YEAR
CONSTRUCTION COST	12464.55	0.0%	+8.4%
COMMON LABOR	24355.78	0.0%	+1.3%
WAGE $/HR.	46.80	0.0%	+1.3%

The Construction Cost Index's annual escalation rose 8.4%, while the monthly component stayed flat.

Building Cost Index — ANNUAL INFLATION RATE — +14.5% SEPT. 2021

1913=100	INDEX VALUE	MONTH	YEAR
BUILDING COST	7214.29	+0.2%	+14.5%
SKILLED LABOR	10880.83	+0.3%	+1.8%
WAGE $/HR.	60.14	+0.3%	+1.8%

The Building Cost Index was up 14.5% on an annual basis, while the monthly component increased 0.2%.

Materials Cost Index — MONTHLY INFLATION RATE — 0.0% SEPT. 2021

1913=100	INDEX VALUE	MONTH	YEAR
MATERIALS COST	4933.04	0.0%	+37.6%
CEMENT $/TON	150.48	+2.3%	+1.3%
STEEL $/CWT	71.49	+1.9%	+28.3%
LUMBER $/MBF	1054.24	−3.1%	+64.3%

The MCI stayed flat since last month, while the annual escalation rate increased 37.6%.

Escalation is cyclical and is not 2.8% per year.

Consider Monte Carlo simulation for forward pricing.

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Escalation

Actual inflation from 2006 and on is used. Prior to 2006 is not readily available.

55

Construction Cost Inflation

Building Cost Inflation

Material Cost Inflation

Cement Cost Inflation

Steel Inflation

550

551

552 Lumber Inflation

650

651

Construction Cost Inflation							
2007	2008	2009	2010	2011	2012	2013	2
-0.2%	8.5%	-1.4%	4.1%	0.8%	1.6%	5.2%	
0.998	1.085	0.986	1.041	1.008	1.016	1.052	1
41.848	45.416	44.797	46.622	47.010	47.784	50.281	5
38.650	41.945	41.374	43.059	43.418	44.133	46.439	4
35.697	38.740	38.212	39.769	40.100	40.760	42.890	4
32.969	35.780	35.292	36.730	37.035	37.646	39.613	3
30.450	33.045	32.595	33.923	34.205	34.769	36.586	3
28.123	30.520	30.104	31.331	31.592	32.112	33.790	3
25.974	28.188	27.804	28.936	29.177	29.658	31.208	3
23.989	26.034	25.679	26.725	26.948	27.392	28.823	2
22.156	24.045	23.717	24.683	24.889	25.299	26.621	2
20.463	22.207	21.905	22.797	22.987	23.365	24.586	2
18.899	20.510	20.231	21.055	21.230	21.580	22.708	2

Supporting Data - Dictionary | Supporting Data - Salvage Value | Supporting Data - Steel Work | NASA Inflation | ENR Inflation | Discount Factors

Decision Analysis

Cost Benefit Analysis

Putting it all together for the decision makers

Benefit in time period t

1. Recurring, or operations and sustainment (O&S), cost reduction
2. Cost avoidance

B_t

C_t

Cost in time period t

Implementation cost

Return on Investment (ROI)

$$NPV = \sum_{i=1}^{20} \frac{B_t - C_t}{(1+r)^t}$$

Discount rate

Office of Management and Budget (OMB) Circular A-94

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Outlay and Escalation

Outlay based on Saturn IC

NASA New Start Inflation (NNSI) used, but will be customizable based on applicability

COST AND SCHEDULE RISK IMPERATIVE

1

RISK IS A MUST, NOT AN OPTION

High degree of cost and schedule growth in completed projects means that there is a great deal of resource risk

2

MORE THAN JUST AVERAGES

It is not sufficient to develop a single point estimate of cost or schedule

"Projects that are based on averages are, on average, behind schedule and beyond budget." – Sam Savage, *The Flaw of Averages*

3

NEEDS TO BE QUANTITATIVE

Qualitative risk assessment results in significant underestimation of risk

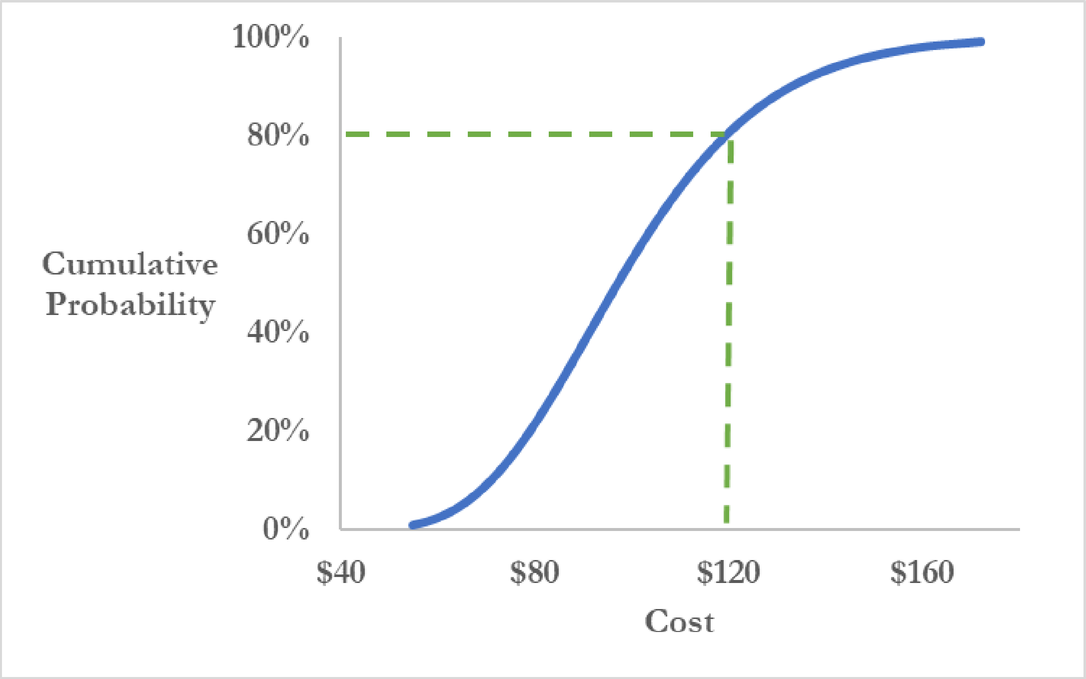
Need to move beyond the risk matrix and robustly assess cost and schedule risk with a quantitative analysis

4

S-CURVES

Cost and schedule risk are typically displayed graphically as "S-curves"

Provides probability that cost/schedule will not exceed a specified value



"Repent, while there is still time." Stephen A. Book, Ph.D.

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CALIBRATING RISK ANALYSIS TO HISTORICAL COST GROWTH

Solving the Risk Underestimation Problem

COST AND SCHEDULE GROWTH

Cost growth and schedule delays occur because risks are realized – they represent risk in action.

FITTING THE DATA

Historical cost growth and schedule slip data closely follow three-parameter lognormal distributions (see example for cost growth data on the right)

CALIBRATION

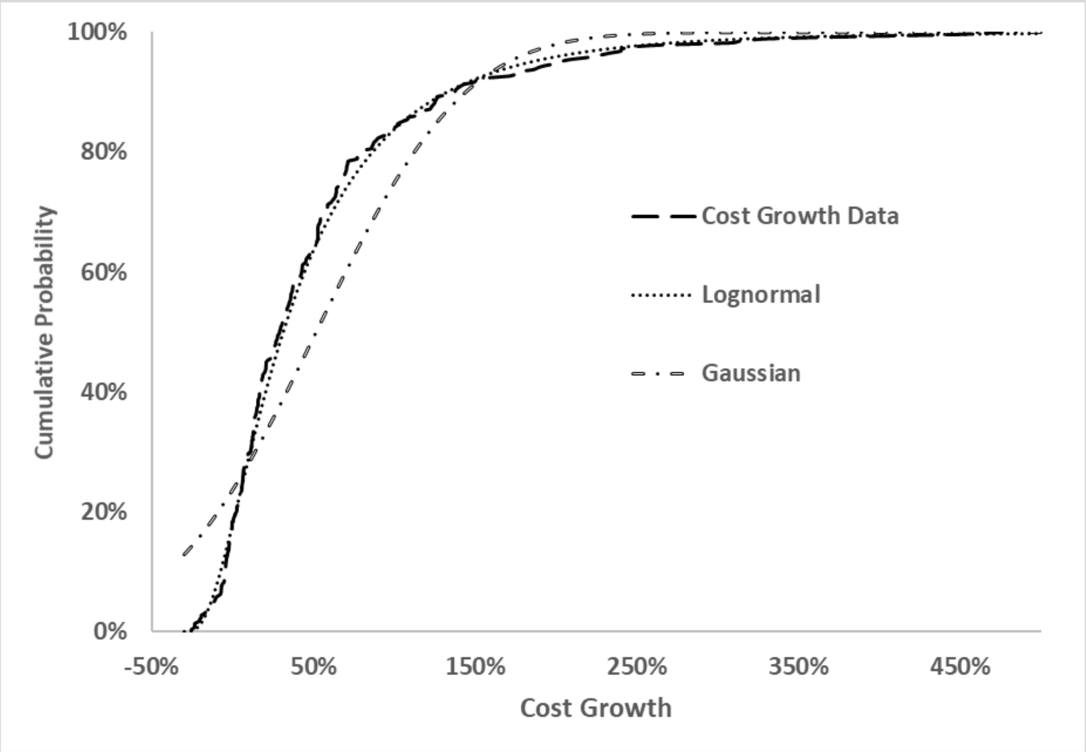
Using the parameters for this lognormal can provide cost and schedule risk distributions

Three inputs –

Location of point estimate (e.g., percentile, mean)

Amount of variation (coefficient of variation)

Minimum (best possible underrun)



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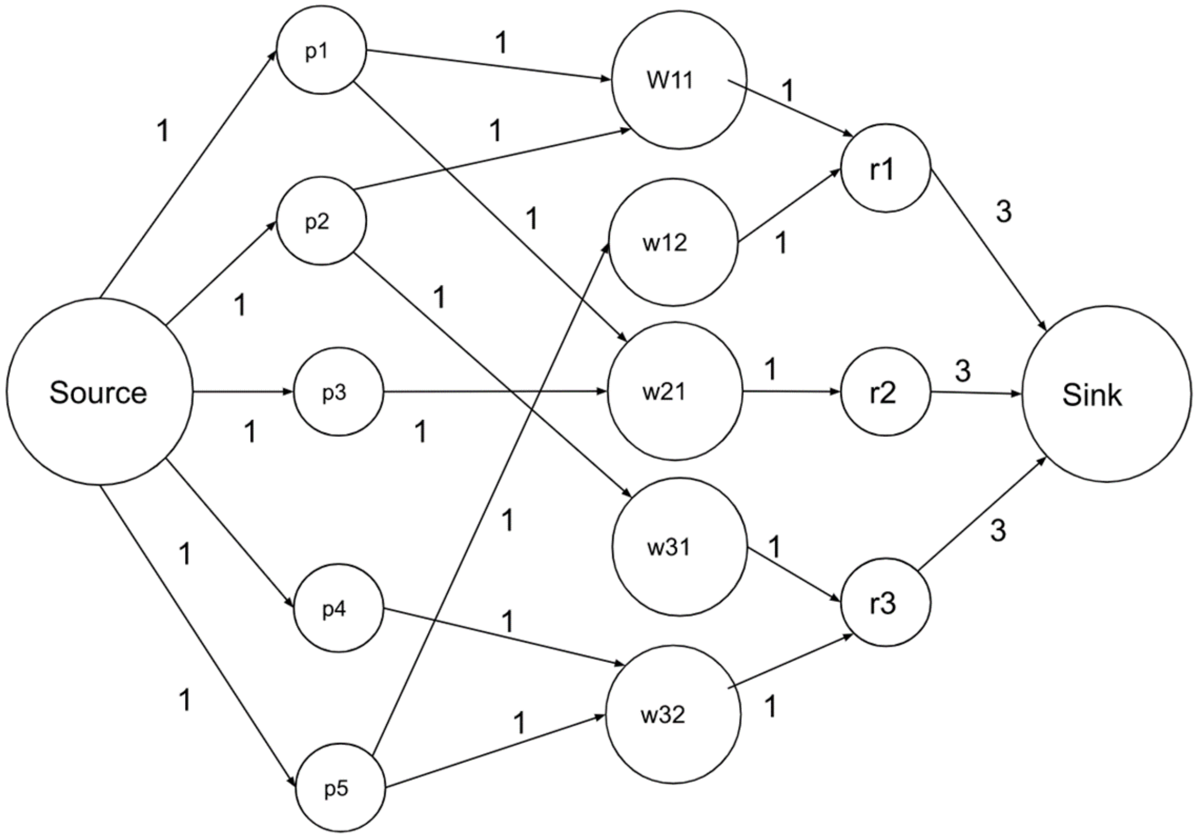
Throughput Analysis

THROUGHPUT ANALYSIS

HOW MUCH CAN BE ACCOMPLISHED IN A YEAR?



IMPORTANT METRIC

The number of test runs that can be conducted in one year is an important metric.

Can be used to assess what investments in facilities can do to improve the amount of testing that can be conducted

CONSTRAINTS

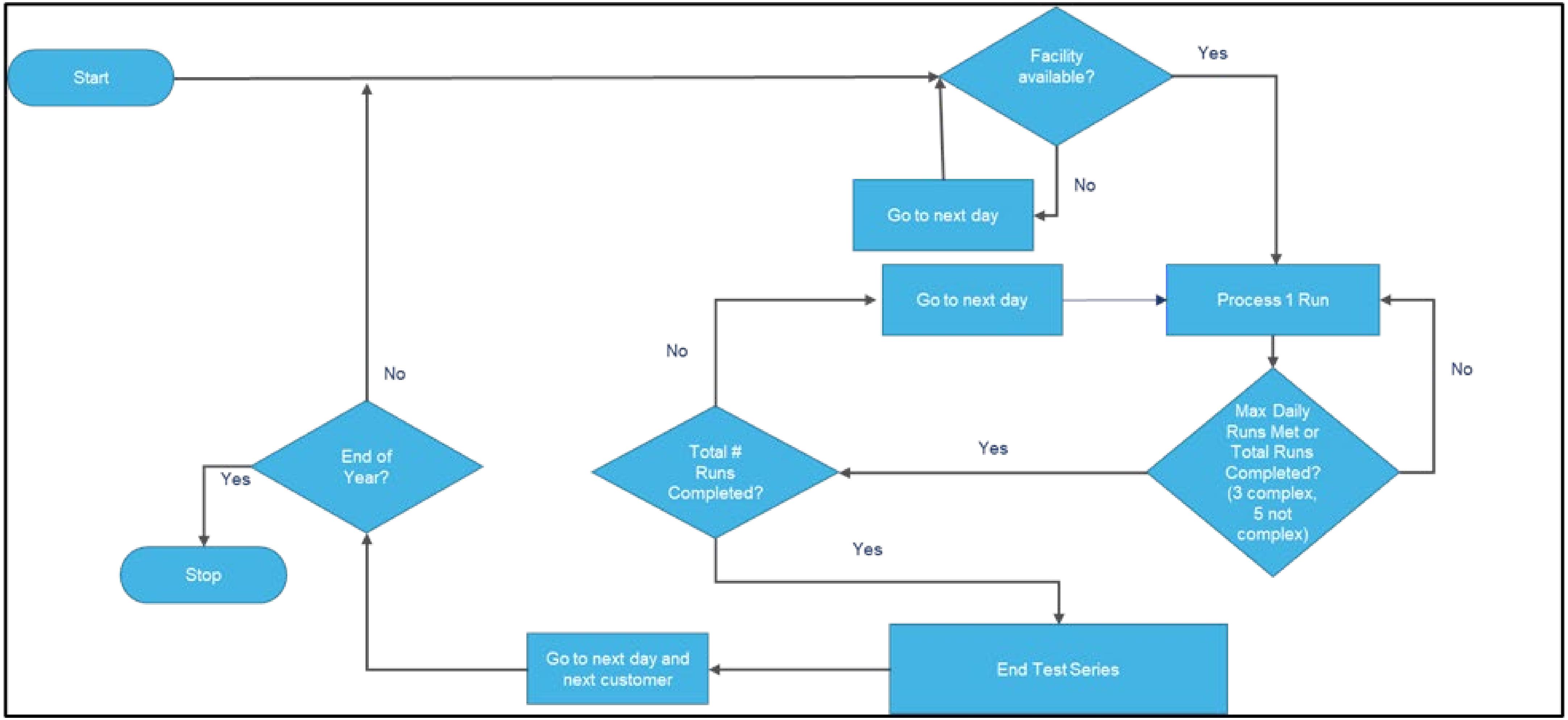
There are a variety of system constraints, such as availability of the test facility, customer availability, and the need for special test set ups that affect throughput

SIMULATION

As the analysis is complex and there is uncertainty in a variety of factors that influence throughput, we analyze the throughput with simulation

All results presented are notional and the simulations are scripted in the R programming language

Test Flow



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MODEL INPUTS

AVAILABILITY

Is the facility available – aging infrastructure means that there are periodic downtimes that cannot be predicted with certainty

COMPLEXITY

Is the model a complex one, which could allow up to three runs per day, or a simple one, which could allow up to five test runs per day

80% of customers require complex testing

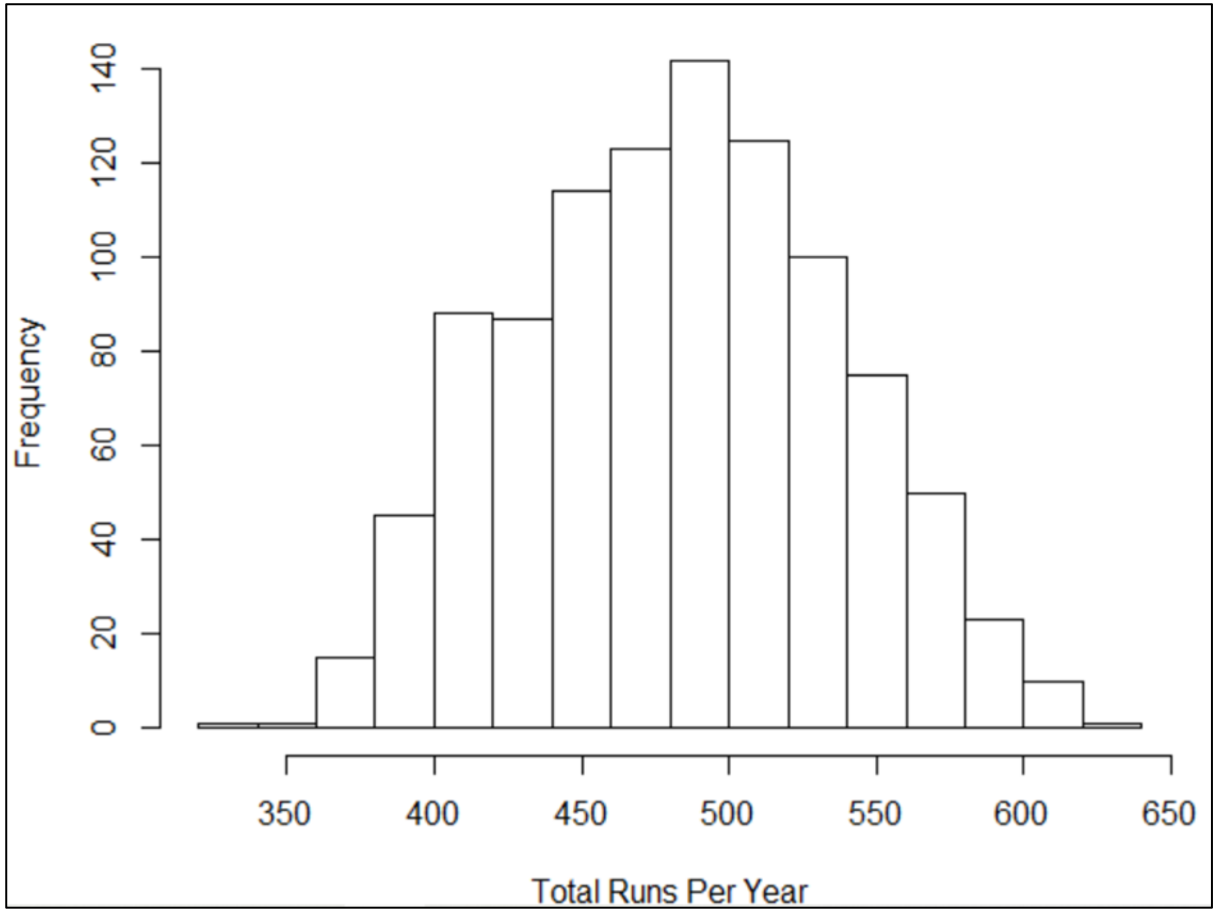
DEMAND

How many customers are there in a year, and how many test runs does each customer need? Both vary and cannot be predicted in advanced

PARALLEL OPERATIONS

There are four facilities and we assume these operate in parallel

SIMULATION – STATUS QUO



PARAMETERS

We simulate the annual number of test runs 1,000 times in order to capture the influence of uncertainty

With 10 government holidays and no weekend work, we assume there are 250 working days in a year

AVAILABILITY

Status quo – 20% for facility 1, 20% for facility 2, 30% for facility 3, and 40% for facility 4

Facility demand – 65% of customers want to use facility 1, while 15% want to use facility 2, 15% want to use facility 3, and 5% want to use facility 4

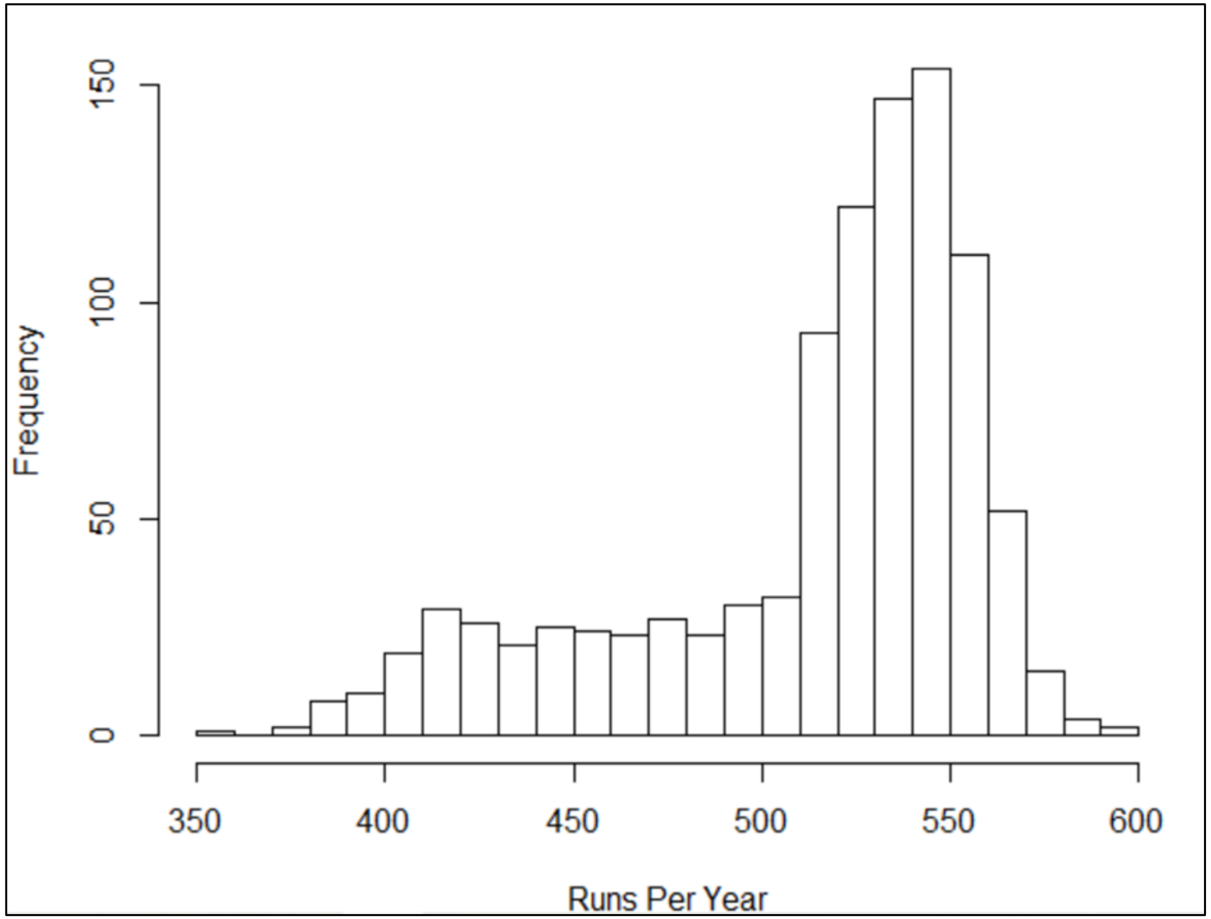
DEMAND

Number of customers varies uniformly from 50 to 100; number of test runs per customers varies uniformly from 4 to 12

RESULTS

Mean number of test runs per year is 483

SIMULATION – WITH INVESTMENTS



CHANGES

With facilities investments, throughput should improve as availability increases

AVAILABILITY

With investments, facilities 1 and 2 are each available 80% of the time and facility 3 is available 60% of the time – facility 4 is shut down

Facility demand – 60% of customers want to use facility 1, while 30% want to use facility 2 and 10% want to use facility 3

CETERIS PARIBUS

We hold the other inputs as constant

RESULTS

Mean number of test runs per year is increase to 514

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Q & A

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