Estimating Prototype Air Vehicle Development Costs at the Skunk Works®

The Sequel

9 September 2015

Wayne Wright
Value Engineer Senior Staff

Summary

The level 2 prototype model labor cost estimating relationship equations upgrade addresses the problem of the lack of recent air vehicles in prior models, including the absence of missiles and unmanned air vehicles. With this upgrade, the number of observations increases from 15 to 24, with the years of first flight now ranging between 1944 and 2009.

The inclusion of air vehicles created within the past 25 years brings to light the effect of technical and manufacturing advances with respect to deriving revised cost estimating relationships. Combined with the increased diversity in air vehicle missions and reduced commonality between the database observations, it becomes harder to predict labor costs using a series of equations, particularly due to difficulty in finding statistically significant independent variables. The result is a slight decrease in model accuracy and precision.

To offset this, we introduce the ability to apply factors based on specific air vehicle actual performance as compared to model prediction. For example, we can now tailor a Next Generation Fighter aircraft estimate to more closely align with YF-22A ATF or X-35 actual performance or both.

Aircraft Programs Used in the Model

XP-80 Lulu Belle
(1944)

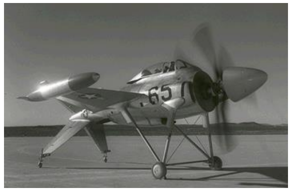
XP2V-1 Neptune
(1945)


XR6O-1 Constitution
(1946)


Model 75 Saturn
(1947)


XF-90
(1949)

XF-104n Starfighter
(1954)


XFV-1 Pogo
(1954)


YC-130 Hercules
(1954)

U-2
(1955)


JetStar
(1957)

LASA-60 Santa Maria
(1959)


XH-51A
(1962)

XV-4A Hummingbird
(1962)


L-286
(1965)

AH-56A Cheyenne
(1967)

XV-4B Hummingbird
(1968)

YF-16
(1973)

Have Blue
(1977)


YF-22A ATF
(1990)

AGM-158 JASSM
(1999)

X-35
(2000)

P-175 Polecat
(2005)

RATTLRS
(no flight test)

X-55
(2009)

Number of observations increases from 15 to 24

Skunk Works

Models Comparison

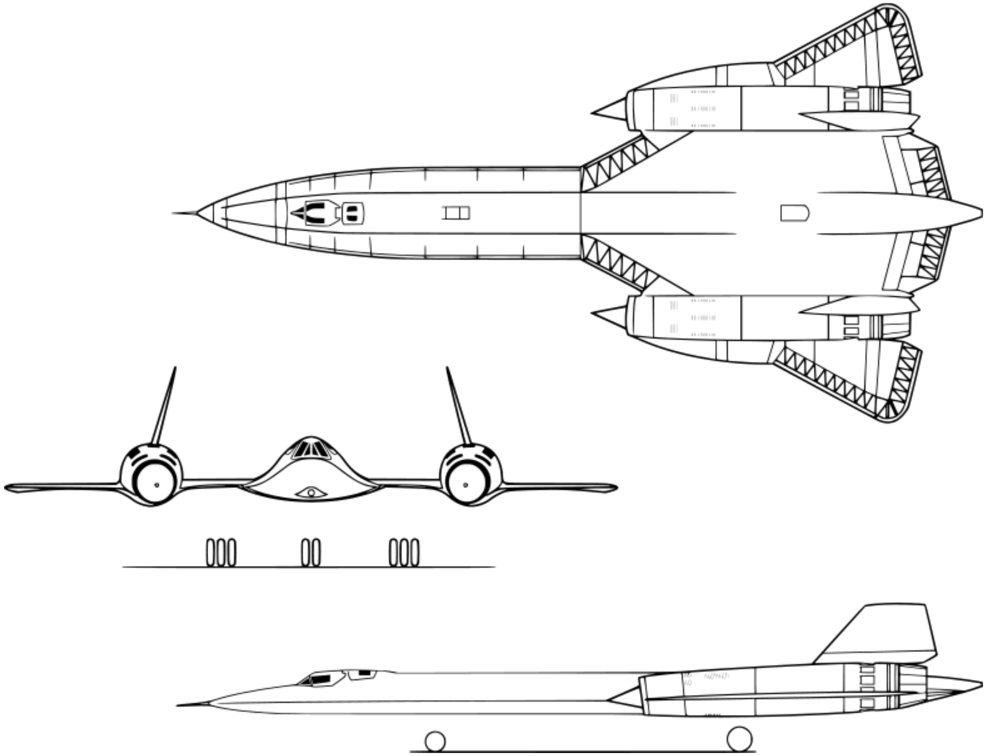
Item	Old	New
Number of Observations	15 (13 aircraft, 2 “virtual” aircraft)	24 (21 aircraft, 2 missiles, 1 UAV)
Years of First Flight Range	1946 – 1990	1944 – 2009
Aircraft Types	5	10
Empty Weight Range (pounds)	2,642 – 124,306	880 – 124,306
Speed Range (Mach)	0.23 – 2.20	0.22 – 3.40
Programmatic Variable	12 experimental, 1 pre-production	20 experimental, 4 pre-production
Requirements Variable	2 minimum, 11 normal	4 minimum, 20 normal
Skin	13 metallic	21 metallic, 3 composite
Goodness of Fit Range (r^2)	0.64 – 0.99	0.62 – 0.94
Goodness of Fit (median CER equation r^2)	0.89	0.83
Accuracy-Bias (prediction under/over actual)	6 under / 7 over	9 under / 15 over
Accuracy-Error (median observation error from zero)	+3.0%	+6.4%
Precision (1/2 of predictions are within…of actual)	16.6%	19.5%
Precision (3/4 of predictions are within…of actual)	20.2%	25.2%

Increase in air vehicle variety and reduced commonality yields a decrease in model accuracy and precision

Skunk Works

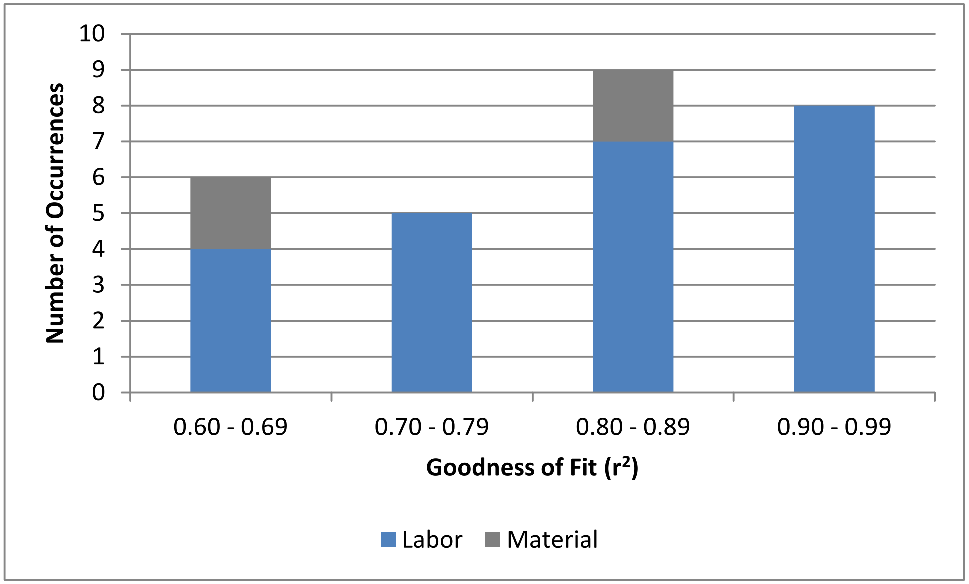
In-House Labor Cost Estimating Relationship (CER) Equation Independent Variables

- **Weight**
  - Total manufacturer's empty weight
  - Manufacturing weight
- **Schedule**
  - Total program
  - Time to first flight
- **Vehicle complexity**
- **Thrust**
- **System dummy variable**
  - Manned vs. unmanned
- **Programmatic dummy variable**
  - Experimental vs. pre-production
- **Requirements dummy variable**
  - Reduced vs. normal
- **Skin dummy variable**
  - Metallic vs. composite
- **Supersonic fighter dummy variable**
- **Stealth air vehicle dummy variable**



Skunk Works

CER Equations Goodness of Fit



Minimum r^2 = 0.60 Median r^2 = 0.83 Maximum r^2 = 0.94

15 of 24 labor CER equations have r^2 > 0.80

Flashback:
Model Labor Estimating Concept

Purely fictional exercise: Management approaches Estimating to request development and first unit recurring cost for a composite version of the L-1011 TriStar. Project is dubbed "LM-21 BlueStar"

In-House Development and First Unit Manufacturing Labor					
Function	**Low**	**Mid**	**High**	***Program***	**UM**
Design	1,173,000	1,244,000	1,324,000	*1,324,000*	hr
Design Support	129,000	166,000	602,000	*396,000*	hr
Software	250,000	500,000	1,000,000	*500,000*	hr
Ground Test	221,000	655,000	3,306,000	*380,000*	hr
Flight Test	472,000	668,000	1,302,000	*485,000*	hr
Logistics	8,000	65,000	98,000	*48,000*	hr
Tooling	1,707,000	1,963,000	2,261,000	*1,707,000*	hr
Devel. Material Mgmt.	114,000	177,000	279,000	*175,000*	hr
Manufacturing T1	1,084,000	1,344,000	2,734,000	*1,085,000*	hr
QA T1	113,000	118,000	153,000	*113,000*	hr
Mfg. T1 Material Mgmt.	90,000	131,000	193,000	*122,000*	hr
Total Labor	**5,361,000**	**7,031,000**	**13,252,000**	***6,335,000***	**hr**

"Program" column allows for the estimator or requestor to choose values based on additional information or judgment

Three sets of cost estimating relationship equations for each labor function yield low, mid, and high estimates

Skunk Works

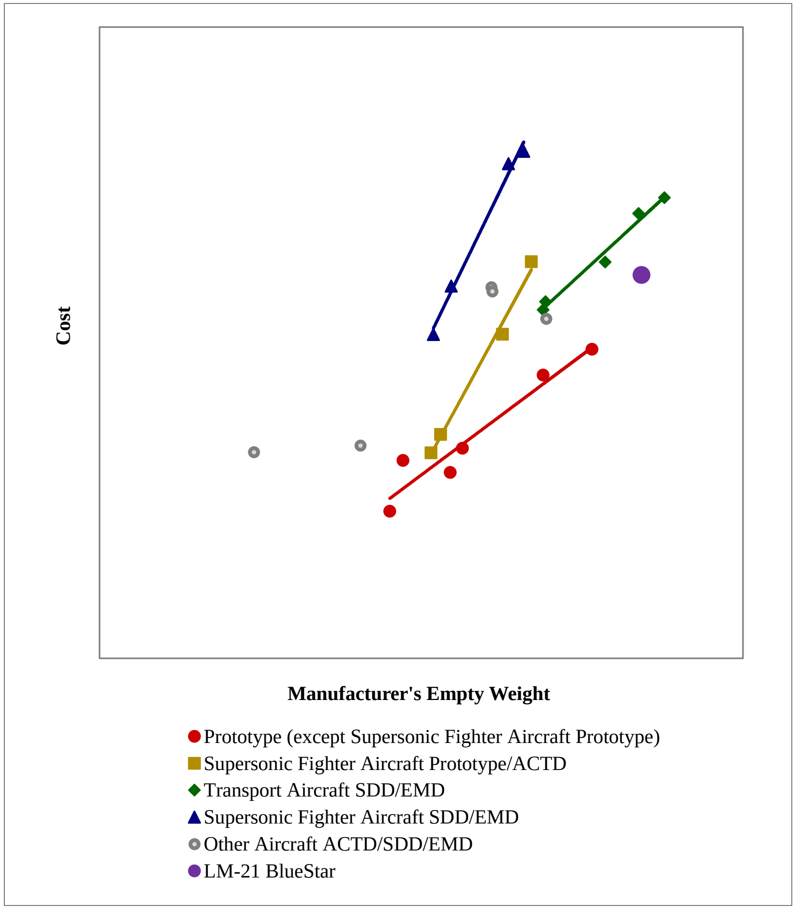
Flashback:
Sample Supplier Input Worksheet: "LM-21 BlueStar"

Work breakdown structure is a function of what system is used: aircraft, unmanned aerial vehicle, or missile

WBS #	Item	Low	Mid	High	Program	UM	Std. Dev.
1.0	**Aircraft System**						
1.1	Air Vehicle						
1.1.1	Airframe	0	0	0	*0*	2015$	0.426
1.1.2	Propulsion	0	0	0	*0*	2015$	0.426
1.1.3	Vehicle Subsystems	156,748,000	240,000,000	367,469,000	*240,000,000*	2015$	0.426
1.1.4	Avionics	13,062,000	20,000,000	30,622,000	*20,000,000*	2015$	0.426
1.1.5	Armament/Weapons Delivery	0	0	0	*0*	2015$	0.426
1.1.6	Auxiliary Equipment	0	0	0	*0*	2015$	0.426
1.1.7	Furnishings and Equipment	0	0	0	*0*	2015$	0.426
1.1.8	Air Vehicle Software	0	0	0	*0*	2015$	0.426
1.1.9	Air Vehicle IAT&C	0	0	0	*0*	2015$	0.426
			0		*0*		0.426
			0		*0*		0.426
			0		*0*		0.426
			0		*0*		0.426
			0		*0*		0.426
			0		*0*		0.426
			0		*0*		0.426
			0		*0*		0.426
			0		*0*		0.426
			0		*0*		0.426
			0		*0*		0.426
1.2	System Engineering	0	0	0	*0*	2015$	0.426
1.3	Program Management	0	0	0	*0*	2015$	0.426
1.4	System Test and Evaluation	0	0	0	*0*	2015$	0.426
1.5	Training	0	0	0	*0*	2015$	0.426
1.6	Data	0	0	0	*0*	2015$	0.426
1.7	Peculiar Support Equipment	0	0	0	*0*	2015$	0.426
1.8	Common Support Equipment	0	0	0	*0*	2015$	0.426
1.9	Operational/Site Activation	0	0	0	*0*	2015$	0.426
1.10	Industrial Facilities	0	0	0	*0*	2015$	0.426
1.11	Initial Spares and Repair Parts	0	0	0	*0*	2015$	0.426
	Total Supplier Development	**169,810,000**	**260,000,000**	**398,091,000**	***260,000,000***	**2015$**	

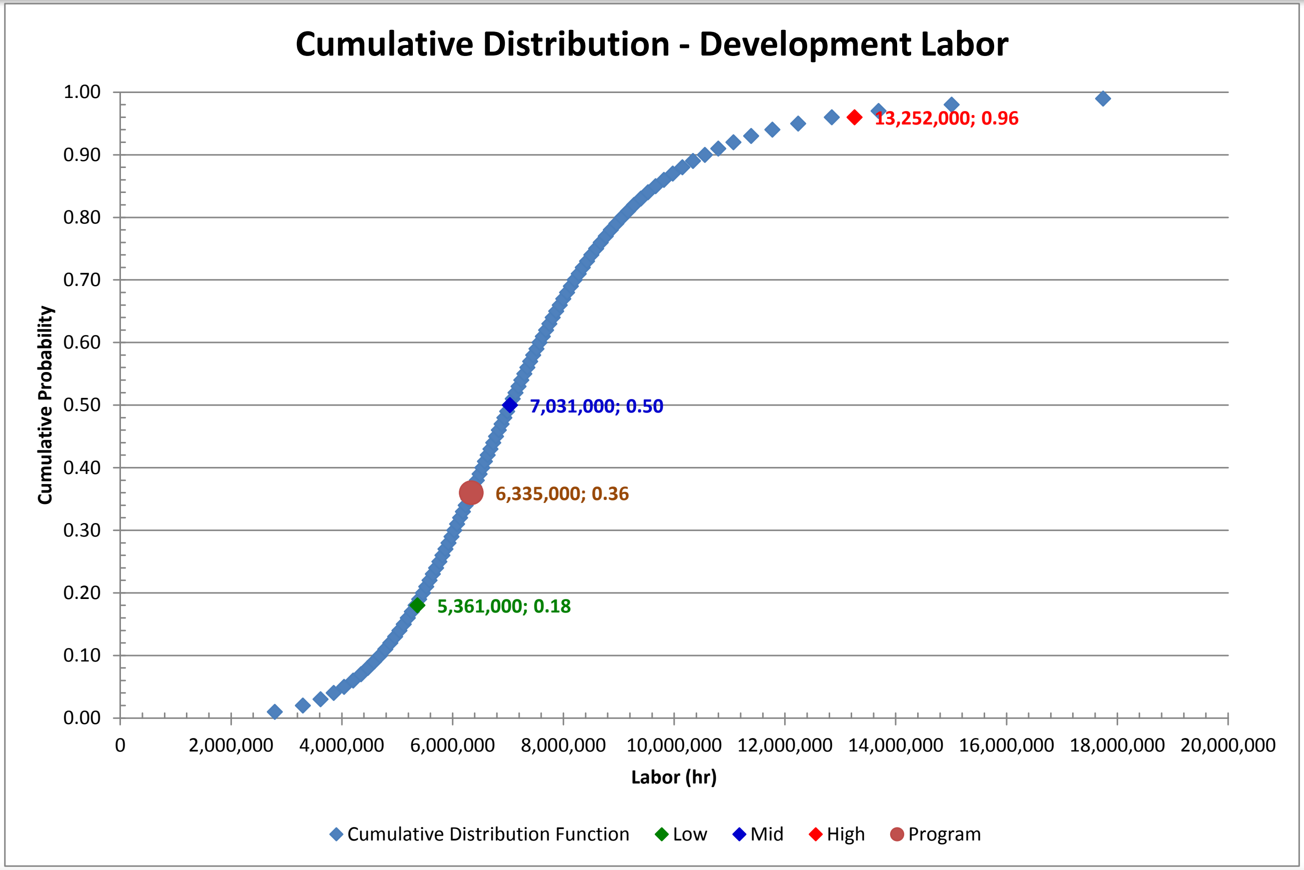
The estimator can apply discrete inputs directly to the worksheet or link bill of material or CER equation data from a separate worksheet

Comparing "LM-21 BlueStar" Result Against Other Program Actual Performance



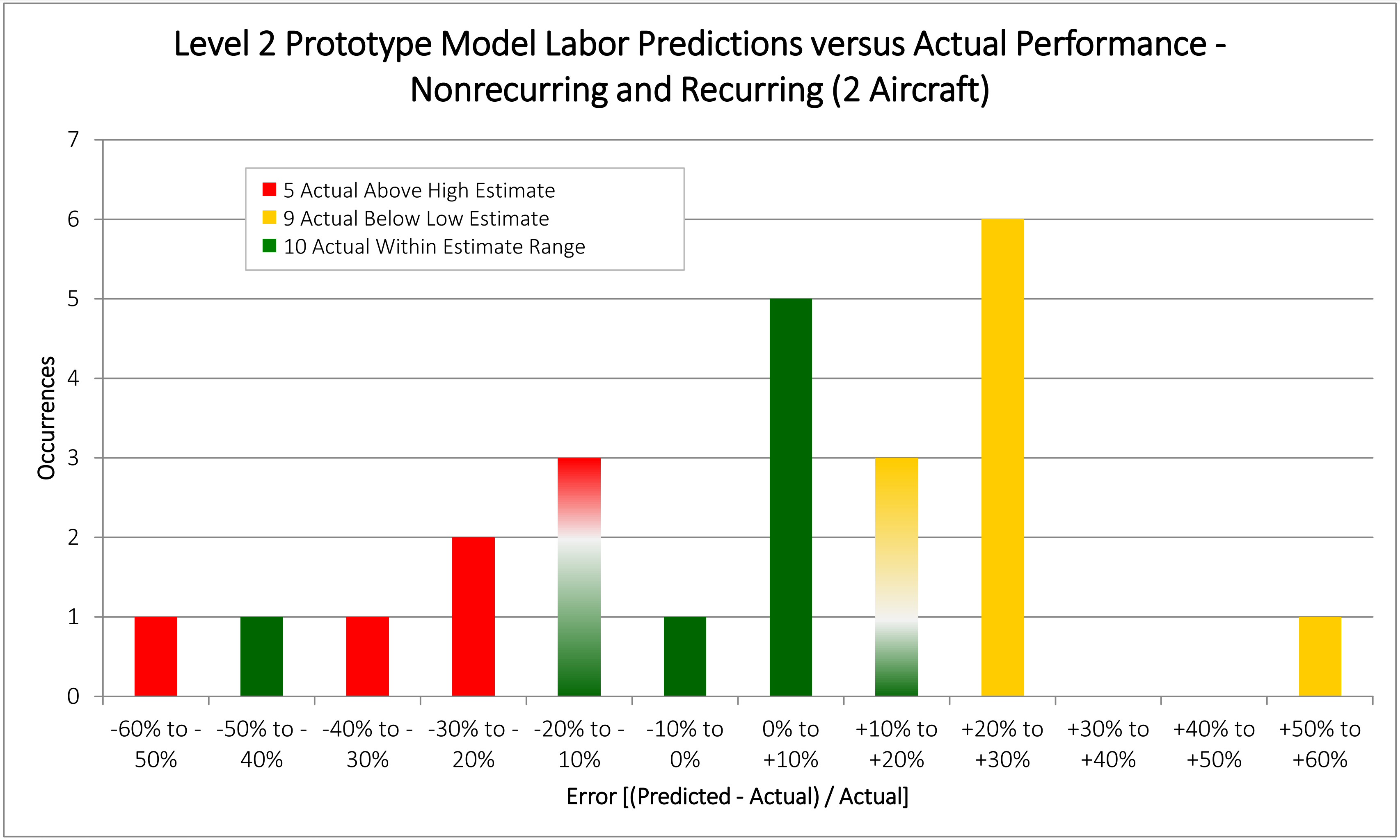
Separating Aircraft by Type and Program Phase Dramatically Improves Goodness of Fit Results

Flashback: Labor Risk Analysis: "LM-21 BlueStar"



The lognormal cumulative distribution function is centered on the mid value with the standard error based on the regression line shown on the previous slide. Low, high, and program values are superimposed on the s-curve

Model Validation



¼ of the observations fall within 10%, ½ fall within 20%

Skunk Works

Calibration Factors Introduction into Model

Program Designation	Composite Factor	No Calibration Factor	XP-80	XP2V-1	XR6O-1	Model 75	XF-90	XF-104n	XFV-1	YC-130	U-2
Name of Aircraft			Lulu Belle	Neptune	Constitution	Saturn		Starfighter	Pogo	Hercules	
Type of Aircraft			Patrol	Patrol	Transport	Transport	Fighter	Fighter	Vert Ftr	Transport	Recon
Year Of First Flight			1944	1945	1946	1947	1949	1954	1954	1954	1955
Allocation	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
D_Lab1	0.6387	1.0000	1.0588	1.0000	1.0135	0.0452	0.8291	1.0933	0.0851	0.7389	1.0000
D_Lab2	1.1305	1.0000	0.8345	1.0000	1.2109	0.1745	1.0394	1.1702	0.4959	1.0611	1.0000
D_Lab3	0.1402	1.0000	0.9220	1.0000	1.1967	0.1169	0.9871	1.1513	0.3072	0.9985	1.0000
DS_Lab1	0.6434	1.0000	0.7461	1.0000	1.4340	0.0172	0.0741	0.1282	0.3374	1.3158	1.0000
DS_Lab2	1.1582	1.0000	0.5589	1.0000	1.4410	0.0537	0.2545	0.2953	0.6748	1.4223	1.0000
DS_Lab3	1.4048	1.0000	0.6228	1.0000	1.3674	0.3097	0.3262	0.9923	0.9121	1.0465	1.0000
GT_Lab1	1.3075	1.0000	0.3778	1.0000	0.1783	1.4439	0.9304	1.2882	1.1521	0.5788	1.0000
GT_Lab2	1.3422	1.0000	0.2537	1.0000	0.3912	1.2469	0.9308	1.2507	1.0931	0.7463	1.0000
GT_Lab3	1.4259	1.0000	0.4674	1.0000	0.7773	0.9338	1.1717	1.3703	1.2702	1.0718	1.0000
FT_Lab1	0.7887	1.0000	0.3829	1.0000	0.6433	1.2342	0.8404	0.7436	0.9757	0.9170	1.0000
FT_Lab2	0.8385	1.0000	0.2637	1.0000	0.9423	1.0298	0.8545	0.6372	0.9126	1.0785	1.0000
FT_Lab3	0.8039	1.0000	0.4898	1.0000	0.6801	1.3310	0.5064	1.3203	0.6918	0.9038	1.0000
Log_Lab1	0.3985	1.0000	1.0000	1.0000	0.4309	1.0000	1.0000	0.0000	1.2903	0.6750	1.0000
Log_Lab2	0.0040	1.0000	1.0000	1.0000	1.2329	1.0000	1.0000	0.0000	1.3094	1.0875	1.0000
Log_Lab3	0.9544	1.0000	1.0000	1.0000	0.6875	1.0000	1.0000	0.0000	1.3459	0.7514	1.0000
Tool_Lab1	1.2722	1.0000	0.0058	1.2009	0.3621	1.0000	0.4722	0.7803	0.9139	0.9756	1.3187
Tool_Lab2	1.3669	1.0000	0.0357	1.3200	0.5339	1.0000	0.7148	1.0208	1.1314	1.1422	1.4034
Tool_Lab3	0.1200	1.0000	0.0395	1.3533	0.6713	1.0000	0.7755	1.0547	1.1587	1.2126	1.4113
Mfg_Lab1	1.0618	1.0000	1.0633	1.3366	0.7141	1.0988	0.7357	0.9796	1.1625	0.8859	0.7860
Mfg_Lab2	1.0498	1.0000	0.9654	1.3285	0.7668	1.0354	0.6918	0.9004	1.0778	0.9009	0.6836
Mfg_Lab3	1.1497	1.0000	0.9548	1.3330	0.7549	1.1107	0.8764	0.8432	0.6586	0.9985	0.4509
QA_Lab1	0.6326	1.0000	1.4057	1.0000	1.0054	0.7603	0.9704	1.0047	1.0147	1.0413	0.8377
QA_Lab2	0.8120	1.0000	1.3971	1.0000	1.0379	0.7432	0.9609	0.4202	0.9865	1.0616	0.7990
QA_Lab3	0.7275	1.0000	1.4144	1.0000	1.1040	0.8428	0.8180	0.8115	0.8642	1.0923	0.7836
DDS_Matl	1.3579	1.0000	1.0000	1.0000	1.3522	1.0000	1.4395	1.4126	0.0000	1.4445	1.0000
FT_Matl	1.1791	1.0000	1.0000	1.0000	0.8525	1.0000	1.4389	0.5949	0.0000	1.1095	1.0000
Tool_Matl	1.0000	1.0000	1.0000	1.0000	1.2509	1.0000	1.0962	1.1750	1.0000	0.8026	1.0000
Mfg1_Matl	1.2749	1.0000	0.9851	1.0000	1.0409	1.0000	0.3989	0.6275	1.1427	0.5024	1.0000

Program Designation		LASA-60	XH-51A	XV-4A	L-286	AH-56A	XV-4B	YF-16		YF-22A	AGM-158	X-35	P-175		X-55
Name of Aircraft	JetStar	Santa Maria		Hummingbird		Cheyenne	Hummingbird		Have Blue	ATF	JASSM		Polecat	RATTLRS	
Type of Aircraft	Transport	Utility	Helicopter	VTOL	Helicopter	Helicopter	VTOL	Fighter	Fighter	Fighter	Missile	Fighter	UAV	Missile	Transport
Year Of First Flight	1957	1959	1962	1962	1965	1967	1968	1973	1977	1990	1999	2000	2005		2009
Allocation	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	100%	0%	0%	0%
D_Lab1	1.2847	1.0000	0.5562	1.0614	1.1981	1.4302	0.5310	1.2554	1.0498	1.4109	1.440	0.638	0.2872	0.7589	0.3879
D_Lab2	1.1056	1.0000	0.7684	1.1613	1.2131	0.8111	0.8860	1.3554	1.2184	1.0735	1.093	1.130	0.5206	1.3281	0.6975
D_Lab3	1.1957	1.0000	0.6620	1.1190	1.1931	1.4055	0.7570	1.3301	0.2747	1.4379	1.406	0.140	0.4245	1.1389	0.5942
DS_Lab1	1.4426	1.0000	1.2430	0.4639	1.1411	1.4444	1.0738	0.8623	1.2073	1.4379	1.437	0.643	0.8973	0.1517	0.6402
DS_Lab2	1.4433	1.0000	1.3014	0.6149	1.2160	0.9899	1.1764	1.1305	1.2719	1.2227	0.724	1.158	0.8788	0.2773	0.8924
DS_Lab3	1.2723	1.0000	1.4447	0.5559	1.4391	0.7558	0.5260	1.3877	1.2544	1.1978	0.997	1.404	0.6892	0.0281	0.5176
GT_Lab1	1.4446	1.0000	1.1921	0.4994	1.2687	1.4164	0.8803	0.0514	0.5758	1.4401	0.754	1.307	1.2035	1.0030	0.0000
GT_Lab2	1.3073	1.0000	0.9790	0.3303	1.1010	1.4213	0.7602	0.0408	0.4573	1.4296	1.414	1.342	1.4349	0.6381	0.0010
GT_Lab3	1.0509	1.0000	1.1446	0.5513	1.2431	1.0146	1.0034	0.1446	0.7151	0.9973	0.987	1.425	1.4387	0.8118	0.0272
FT_Lab1	1.2513	1.0000	1.4362	0.9157	1.4287	1.2384	1.2355	1.1743	0.9768	1.1917	0.010	0.788	1.0053	1.0000	0.3480
FT_Lab2	1.0943	1.0000	1.4440	0.7417	1.3736	1.2193	1.1631	1.1188	0.8734	1.2579	0.264	0.838	1.4105	1.0000	0.1644
FT_Lab3	1.3095	1.0000	1.4331	0.6679	1.4327	1.2332	0.8757	1.4277	0.4568	1.1953	0.041	0.803	0.7909	1.0000	0.2810
Log_Lab1	1.0000	1.0000	1.0000	1.0000	1.0264	1.2625	1.0000	1.4444	1.4446	1.2806	0.390	0.398	1.0000	0.3467	1.0000
Log_Lab2	1.0000	1.0000	1.0000	1.0000	0.1092	1.2158	1.0000	1.4126	1.4173	1.3936	0.113	0.004	1.0000	1.1336	1.0000
Log_Lab3	1.0000	1.0000	1.0000	1.0000	0.2095	0.6743	1.0000	1.4350	1.4330	1.3384	0.818	0.954	1.0000	1.2832	1.0000
Tool_Lab1	0.8937	0.8688	0.7679	0.8087	0.6827	1.4419	0.7794	1.4035	1.4394	1.4052	1.316	1.272	0.8432	0.0259	0.0000
Tool_Lab2	1.1072	1.1336	1.0473	1.0647	0.9717	0.5340	1.0294	1.4395	1.4150	0.8893	1.362	1.366	1.0867	0.1241	0.0000
Tool_Lab3	1.1457	1.1144	1.0345	1.0725	0.9621	1.4170	1.0515	1.4423	0.9171	1.2045	1.420	0.120	1.1016	0.1043	0.0000
Mfg_Lab1	0.9977	0.7984	1.3026	1.1360	1.1716	1.0146	0.9137	1.1283	1.2911	1.3604	1.084	1.061	0.1893	0.9595	0.1544
Mfg_Lab2	0.9509	0.6222	1.2174	1.0322	1.0535	0.9543	0.8055	1.0688	1.2392	1.3623	1.362	1.049	0.7276	0.7676	0.6998
Mfg_Lab3	1.1315	0.6710	1.2580	0.9527	1.0293	1.0093	0.6525	1.0033	1.2786	1.3878	1.396	1.149	0.7406	0.7965	0.5666
QA_Lab1	0.9970	0.9862	0.8695	1.1195	0.7510	0.5351	1.2356	1.3541	0.4184	1.3652	1.261	0.632	1.0522	1.1804	0.2397
QA_Lab2	0.9908	0.9167	0.8228	1.0864	0.6956	0.5205	1.2109	0.9867	1.1015	1.4167	1.440	0.812	0.9965	1.1204	0.2043
QA_Lab3	1.0421	1.1011	0.8414	0.9820	0.7195	0.5416	1.0456	1.2272	0.8535	1.3898	1.444	0.727	0.8891	0.9601	0.1898
DDS_Matl	1.4445	1.0000	1.4328	1.3865	1.1921	0.0403	1.0434	1.3971	0.0011	1.2793	1.000	1.357	1.1218	1.0000	1.0000
FT_Matl	0.2667	1.0000	1.4392	1.3088	1.3352	1.3372	0.0000	0.0489	0.0001	1.2530	1.000	1.179	1.2928	1.0000	1.0000
Tool_Matl	1.3059	1.0000	1.3570	1.0000	0.5128	1.0000	1.4415	0.0025	1.0000	1.2629	1.000	1.000	0.1141	1.0000	1.0000
Mfg1_Matl	1.2915	1.0000	1.4085	1.0000	1.4411	0.9375	1.3072	1.1442	0.3009	1.1598	1.000	1.274	0.0220	1.0000	1.0000

Program Designation	Composite Factor	X-35
Name of Aircraft		
Type of Aircraft		Fighter
Year Of First Flight		2000
		
Allocation	100%	100%
D_Lab1	0.6387	0.6387
D_Lab2	1.1305	1.1305
D_Lab3	0.1402	0.1402
DS_Lab1	0.6434	0.6434
DS_Lab2	1.1582	1.1582
DS_Lab3	1.4048	1.4048
GT_Lab1	1.3075	1.3075
GT_Lab2	1.3422	1.3422
GT_Lab3	1.4259	1.4259
FT_Lab1	0.7887	0.7887
FT_Lab2	0.8385	0.8385
FT_Lab3	0.8039	0.8039
Log_Lab1	0.3985	0.3985
Log_Lab2	0.0040	0.0040
Log_Lab3	0.9544	0.9544
Tool_Lab1	1.2722	1.2722
Tool_Lab2	1.3669	1.3669
Tool_Lab3	0.1200	0.1200
Mfg_Lab1	1.0618	1.0618
Mfg_Lab2	1.0498	1.0498
Mfg_Lab3	1.1497	1.1497
QA_Lab1	0.6326	0.6326
QA_Lab2	0.8120	0.8120
QA_Lab3	0.7275	0.7275
DDS_Matl	1.3579	1.3579
FT_Matl	1.1791	1.1791
Tool_Matl	1.0000	1.0000
Mfg1_Matl	1.2749	1.2749

Factor = actual performance / model prediction

Inputting X-35 characteristics and setting X-35 calibration factor allocation to 100% would yield X-35 actual performance results

- *The application of a calibration factor will scale the proposed air vehicle off of similar air vehicle actual performance. This should increase the accuracy of our estimate*
- *More than one air vehicle can be used to create a composite series of factors*

Skunk Works