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A Canadian F-35A Joint Strike Fighter Cost Estimation Model

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Defence Research and Development Canada
Recherche et développement pour la défense Canada

Canada

Background

- F-35 Joint Strike Fighter
  - F-35A CTOL
  - F-35B STOVL
  - F-35C CV

- Affordability heralded as the cornerstone of the F-35 program.
  - Over 3000 aircraft planned
  - US / UK / ITA / NLD / TUR / CAN / AUS / DNK / NOR / Israel / others…
- Manufactured by Lockheed Martin / Pratt & Whitney
- System Development Demonstration (SDD) started in 2001
- Low-rate Initial Production started in 2007 (~30 aircraft to date)

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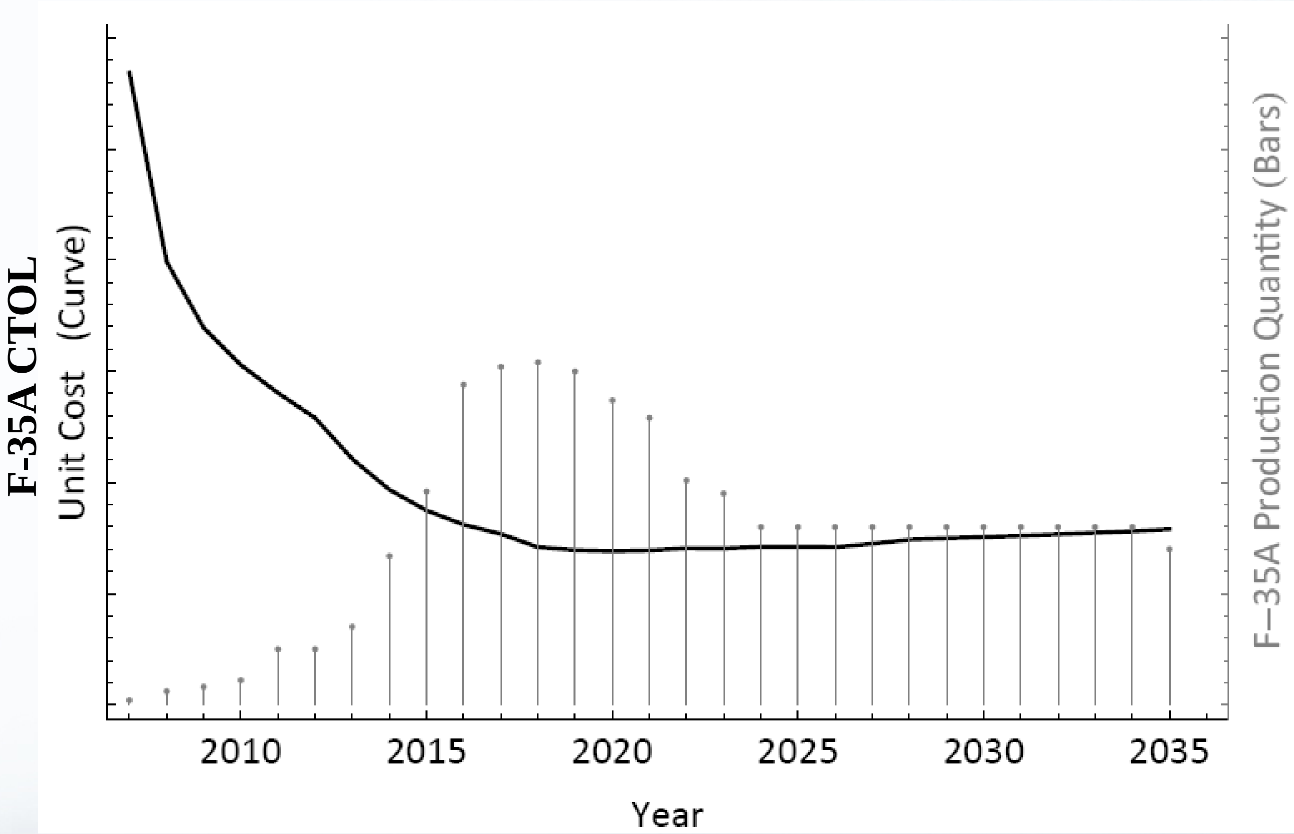
Background

- Canada intends to purchase 65 F-35A CTOL between 2016-2022
- JSF MoU: U.S. JPO provides regular updates to Canada
  - cost projections and production plans, e.g.:



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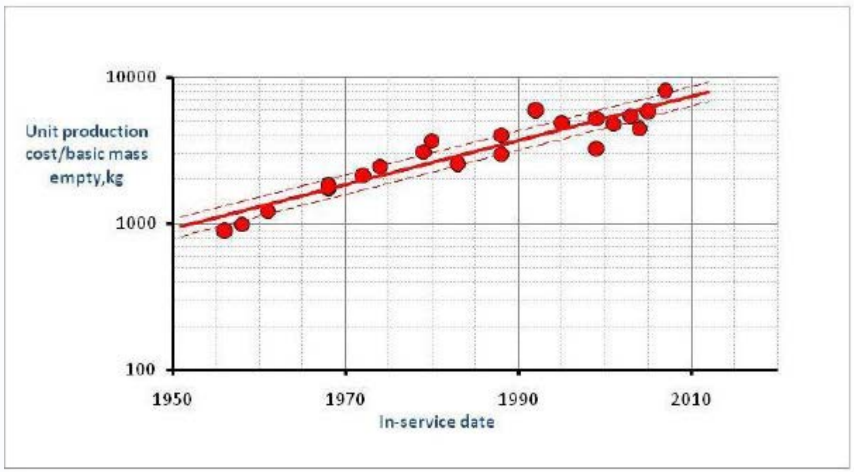
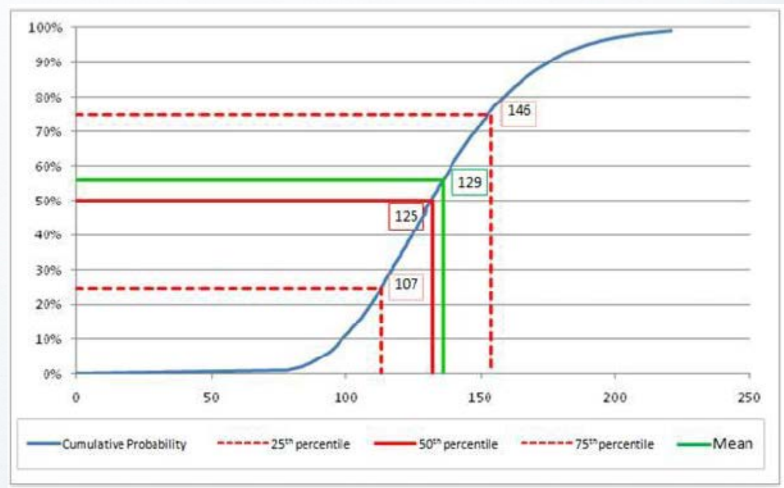
Background

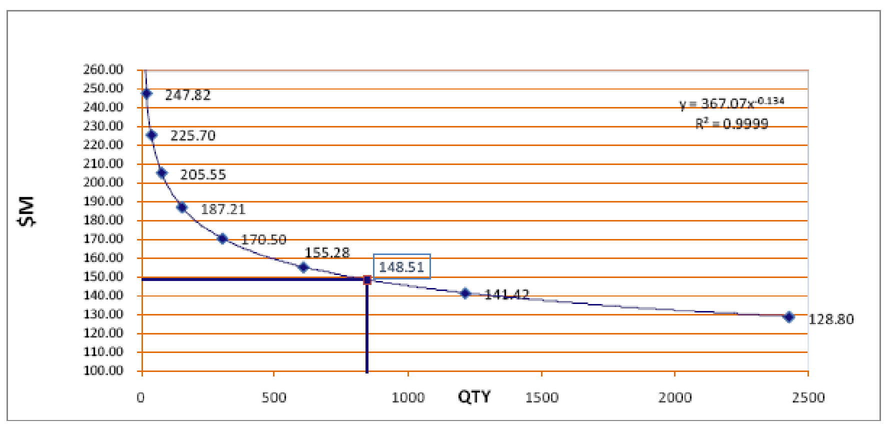
- March 2011: Parliamentary Budget Officer releases report
  - Estimates Canada's avg F-35A URF cost to be $148.5M (2011 USD)

Historical trends in cost for strike/fighter aircraft[48]





Learning curve



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Background

- March 2011: Parliamentary Budget Officer releases report
  - Estimates Canada’s avg F-35A URF cost to be $148.5M (2011 USD)
  - Garnered media attention and was a significant election issue

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Background

- March 2011: Parliamentary Budget Officer releases report
  - Estimates Canada's avg F-35A URF cost to be $148.5M (2011 USD)
  - Garnered media attention and was a significant election issue

- DND response included:
  - Independent reviews of the report's methodologies (DRDC, U of Cranfield)
  - "*Canada's average URF for 65 CTOL aircraft acquired between 2016 and 2022 is at the least expensive time of production. Canada's URF [cost] estimate is due to the delivery times that will be at around the peak of production efficiency*"
  - Canada's URF is estimated to be in the mid-$70M (TY USD)
  - U.S. JPO URF cost graph

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April – July 2011:

- DRDC Center for Operational Research & Analysis
  - Scrutinized PBO methodologies and analysis
  - Began research into developing an independent F-35A cost estimation model
- Canadian F-35A URF cost model
  - Quantity Effects model endorsed by the RAND Corp.
  - Ability to independently generate cost estimates
  - Ability to perform sensitivity analysis
  - High-level risk/uncertainty modelling

INPUT:	JPO Predictions (29yrs) ↓	Actual Completed LRIP Costs ↓
OUTPUT:	Reverse engineered learning slope %s	- Year-by-year projections - Learning slope %s

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Study Objective & Scope

- Objective:
  - Provide Canada's F-35 Project office with model to
    - Defend DND cost estimates
    - Ability to scrutinize U.S. JPO estimates
    - Perform sensitivity analysis
    - Justify contingency levels
  - Due diligence: Multiple Cost Estimates are a Good Thing!
- Scope
  - Limited to predicting cost of F-35A variant
  - High-level model
  - Several assumptions made (next slides)

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Study Assumptions

- Only F-35A **costs** considered and projected
  - Do not included country-specific modifications
- Only F-35A **production numbers** considered
  - STOVL and CV represent nearly 30% of total number of F-35s
  - No attempt to model "*high-degree of commonality*"
  - Exception: F-35C numbers included in engine prediction*
- Only Pratt & Whitney F135 engine considered

***Some analysis showing effect of including F-35B numbers for engine prediction**

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Study Assumptions (cont.)

- Same system (F-35A) produced year after year
- Trends in cost improvement for early LRIP lots will continue
- Some reliance on historical U.S. military aircraft costs
- All costs, inflation, exchange rates had to be masked
- Unit Recurring Flyaway (URF) Costs: as system "*rolls off production line*"
- In this brief we define "Air Vehicle" = URF - Engine

Data (as of 26 June 2011)

- U.S. JPO provided Canada's Project Office with
  - LRIP 1-3 Completion Rates
  - Estimate-at-Completion costs

  } for both airframe and engine

    - Most closely approximate actual production costs
    - Not settlement costs; costs overruns included (but not SDD costs)

			F-35A Air Vehicle		F135 Engine		
Lot	Buy Year	Planned Production	% Completion	EAC Cost	% Completion	EAC Cost	Total EAC Cost
LRIP 1	2007	2	88%	[redacted]	99%	[redacted]	[redacted]
LRIP 2	2008	6	82%	[redacted]	88%	[redacted]	[redacted]
LRIP 3	2009	8	56%	[redacted]	45%	[redacted]	[redacted]

LRIP 1-3 completion rates and estimate-at-completion costs

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Data (as of 26 June 2011)

- U.S. JPO provided Canada's Project Office with

Buy Year (TY)	Partner 1	Partner 2	Partner 3	Canada	Partner 5	Partner 6	Partner 7	Partner 8	FMS 1	Lot Size	Cumulative	Avg Cost Per Unit	F-35C
2007	X									2	2	[redacted]	
2008	X									6	8		
2009	X					X				8	16		
2010	XX					X				11	27		4
2011	XX									25	52		7
2012	XX	X	X							25	77		7
2013	XX	X						X		35	112		19
2014	XX	X	X			X	X	X	X	67	179		14
2015	XX	X	X	X		XX		XX	X	96	275		28
2016	XX	X	XX	X	X	XX	XX	XX	X	144	419		31
2017	XX	X	XX	X	XX	XX	XX	XX		152	571		36
2018	XX	X	XX	XX	XX	XX	XX	XX		154	725		36
2019	XX	X	XX	XX	X	XX	XX	XX		150	875		44
2020	XX	X	XX	XX		XX		XX		137	1012		40
2021	XX	X	XX	X		XX		XX		129	1141		27
2022	XX	X				X		X		101	1242		24
2023	XX	X						X		95	1337		34
2024	XX									80	1417		34
2025	XX									80	1497		34
2026	XX									80	1577		34
2027	XX									80	1657		22
2028	XX									80	1737		
2029	XX									80	1817		
2030	XX									80	1897		
2031	XX									80	1977		
2032	XX									80	2057		
2033	XX									80	2137		
2034	XX									80	2217		
2035	XX									70	2287		
TOTALS:	1763	69	100	65	30	85	56	100	19	2287	2287		475

Used to compute avg URF cost for Canada

mid-$70M (TY USD)

JPO F-35A CTOL production planning profile as of June 2011

The Quantity Effect Model

- Affordability is a pillar of the JSF project
  - Intended to be partly achieved through the large quantity of aircraft produced.
  - A large quantity ordered over time will lead to accumulated experience in producing the same system year after year, reducing the unit cost.

    → **cost improvement effect**

  - The quantity of aircraft produced in a given year (or time period), with high production rates likely reducing the unit cost through greater operating efficiency and the spreading of fixed costs over more units.

    → **production rate effect**

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The Quantity Effect Model

- Endorsed by the RAND Corporation
  - Used in 2007 for F-22A study for U.S. Congress
  - Used in 2008 for historical analysis of military aircraft costs
- Based on two effects:
  - **CI: Cost Improvement (Learning)**: efficiency gained by accumulated experience
  - **PR: Production rate economies of scale:** e.g., spread fixed costs, bulk resource buys

The Quantity Effect Model

$$LAC_i = T_1 \times [\bar{Q}_i(b)]^b \times r_i^c$$

LAC_i is the average incremental cost of the aircraft

T_1 is the cost of the first aircraft produced

$\bar{Q}_i(b)$ is the midpoint of lot i

b is the cost improvement slope (2^b is the slope %)

r_i is the production rate

c is the production rate slope (2^c is the rate %)

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RAND Use & Results

- Historical analysis of military aircraft costs

Arena, M.V., Younossi, O., Brancato, K., Blickstein, I., and Grammich, C.A. (2008), Why Has the Cost of Fixed-Wing Aircraft Risen? A Macroscopic Examination of the Trends in U.S. Military Aircraft Costs over the Past Several Decades, (Report MG-696-NAVY/AF) RAND Corporation, Santa Monica, CA.

	Military Aircraft	Fighter Jets
Mean CI slope %	0.97	0.93
Standard deviation of CI slope %	0.13	n/a
Mean PR slope %	0.89	0.78
Standard deviation PR slope %	0.23	n/a
Number of aircraft	24	6

Historical cost improvement and production rate slope percentages

- F-22A study for U.S. Congress

Younossi, O., Arena, M.V., Brancato, K., Graser, J.C., Goldsmith, B.W., Lorell, M.A., Timson, F., and Sollinger, J.M. (2007), F-22A Multiyear Procurement Program: An Assessment of Cost Savings, (Report MG-664-OSD) RAND Corporation, Santa Monica, CA.

  – Found high correlation production rate and midpoint values
    - Determining learning and production rates slopes simultaneously may be statistically invalid.
    - Solution: use mean historical production rate of **89%** (airframe) and **97%** (engine)

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Application to F-35A

- Multi-Variate Regression:

$$\mathrm{Ln}(LAC_i) = \mathrm{Ln}(T_1) + b \times \mathrm{Ln}(\bar{Q}_i(b)) + c \times \mathrm{Ln}(r_i) + \varepsilon_i$$

LAC_i is the average incremental cost of the aircraft
T_1 is the cost of the first aircraft produced
$\bar{Q}_i(b)$ is the midpoint of lot i
b is the cost improvement slope (2^b is the slope %)
r_i is the production rate
c is the production rate slope (2^c is the rate %)

INPUT:	JPO Predictions (29yrs) ↓	Actual Completed LRIP Costs ↓
OUTPUT:	Reverse engineered learning slope %s	- Year-by-year projections - Learning slope %s

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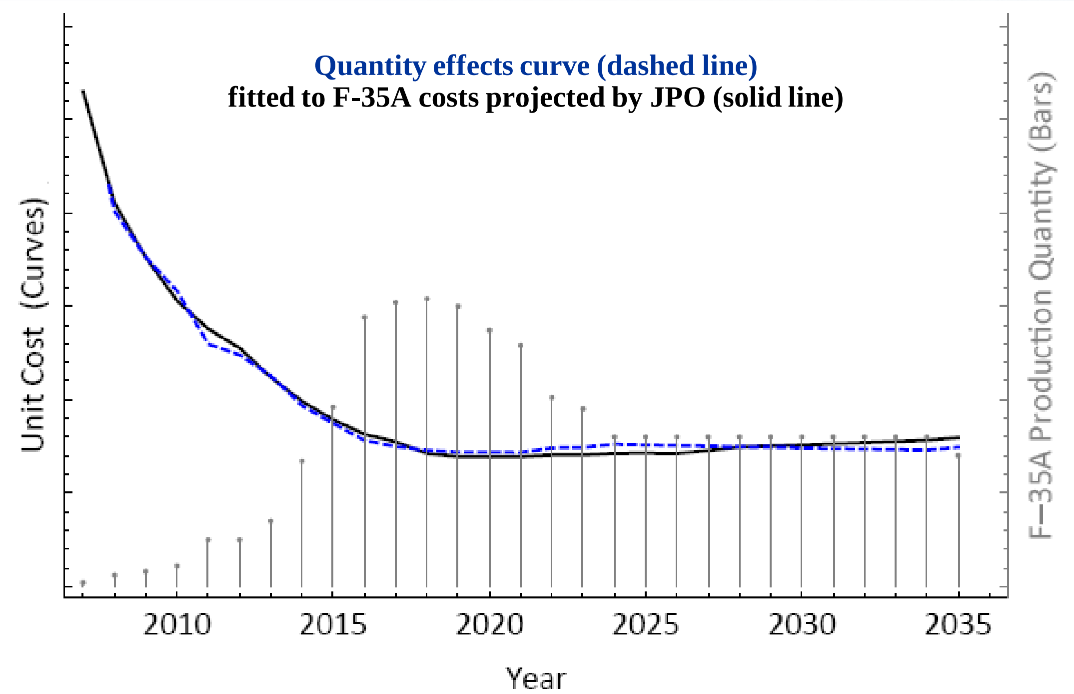
Application to F-35A

- Reverse engineered JPO Predictions (06/11):

INPUT:	JPO Predictions (29yrs) ↓	Actual Completed LRIP Costs ↓
OUTPUT:	Reverse engineered learning slope %s	- Year-by-year projections - Learning slope %s



CI slope = 94%
PR slope = 89%

$R^2 = 0.9999$

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Application to F-35A

- Reverse engineered JPO Predictions (06/11):

INPUT:	JPO Predictions (29yrs) ↓	Actual Completed LRIP Costs ↓
OUTPUT:	Reverse engineered learning slope %s	- Year-by-year projections - Learning slope %s

Parameter	Estimate	Standard Error	95% Confidence Interval	t-Statistic	P-Value
T_1	319.8	10.7	(297.8, 341.8)	29.8	≈ 0
CI Slope %	0.94	0.01	(0.93, 0.95)	162.9	≈ 0
PR Slope %	0.89	0.01	(0.86, 0.91)	85.1	≈ 0

Found to be better fit than if PR slope set to 100%

Presented at the 2012 SCEA/ISPA Joint Annual Conference and Training Workshop - www.iceaaonline.com

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Application to F-35A

- Given LRIPs 1-3, project future costs:

INPUT:	JPO Predictions (29yrs) ↓	Actual Completed LRIP Costs ↓
OUTPUT:	Reverse engineered learning slope %s	- Year-by-year projections - Learning slope %s

		F-35A Air Vehicle		F135 Engine		
Lot	Production	% Completion	EAC Cost	% Completion	EAC Cost	Total EAC Cost
LRIP 1	2	88%	[redacted]	99%	[redacted]	[redacted]
LRIP 2	6	82%	[redacted]	88%	[redacted]	[redacted]
LRIP 3	8	56%	[redacted]	45%	[redacted]	[redacted]

LRIP 1-3 EAC in 2011 USD

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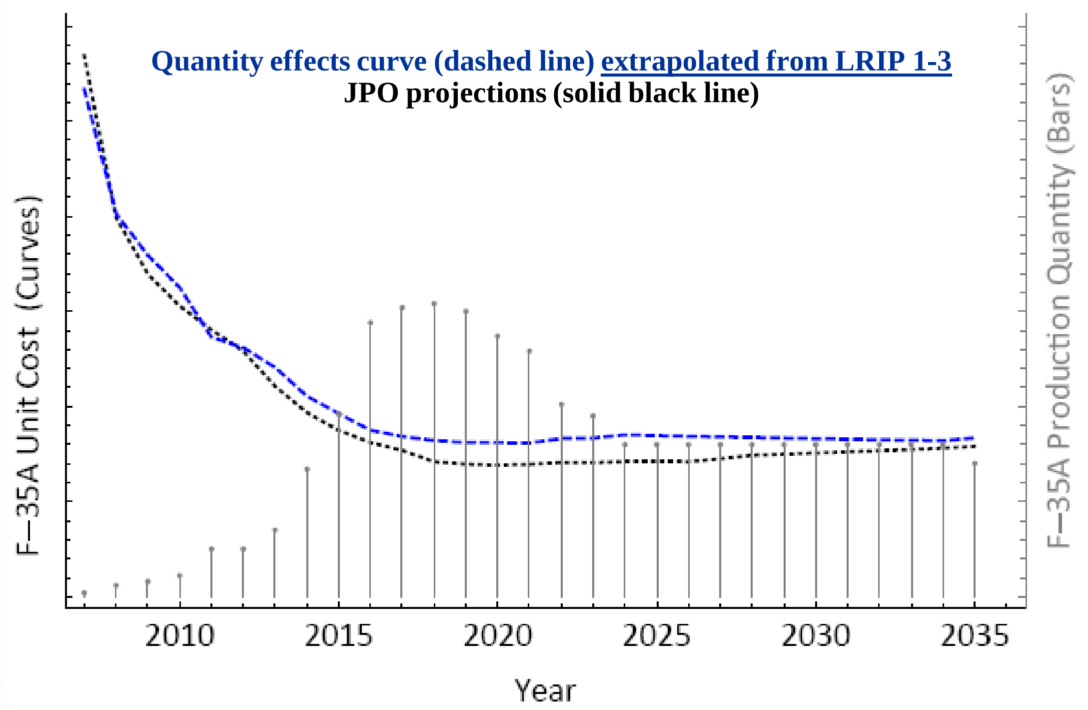
Application to F-35A

- Given LRIPs 1-3, project future costs:

INPUT:	JPO Predictions (29yrs) ↓	Actual Completed LRIP Costs ↓
OUTPUT:	Reverse engineered learning slope %s	- Year-by-year projections - Learning slope %s



Estimated

	F135	Airframe
CI Slope %	0.93	0.95
PR Slope %	0.97	0.89

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Results: Sensitivity Analysis

- What if learning/production efficiencies not achieved?

CI Slope	Production Rate Slope 80%	82%	84%	86%	88%	90%	92%	94%	96%	98%	100%	102%
80%	-71%	-69%	-67%	-65%	-62%	-60%	-56%	-53%	-49%	-45%	-41%	-36%
82%	-68%	-66%	-64%	-61%	-58%	-54%	-51%	-47%	-42%	-37%	-32%	-26%
84%	-65%	-62%	-59%	-56%	-52%	-48%	-44%	-39%	-34%	-28%	-22%	-15%
86%	-61%	-58%	-54%	-50%	-46%	-41%	-36%	-30%	-24%	-17%	-10%	-2%
88%	-57%	-53%	-49%	-44%	-39%	-33%	-27%	-20%	-12%	-4%	4%	14%
90%	-52%	-47%	-42%	-36%	-30%	-23%	-16%	-8%	1%	10%	21%	32%
92%	-45%	-40%	-34%	-28%	-20%	-13%	-4%	6%	16%	27%	39%	52%
94%	-39%	-32%	-25%	-18%	-9%	0%	10%	21%	33%	46%	61%	76%
96%	-31%	-23%	-15%	-6%	4%	14%	26%	39%	53%	68%	85%	103%
98%	-22%	-13%	-4%	7%	18%	31%	45%	59%	76%	94%	113%	134%
100%	-11%	-2%	9%	22%	35%	49%	65%	83%	102%	123%	145%	170%
102%	0%	12%	24%	38%	54%	71%	89%	109%	131%	155%	181%	210%

Canadian URF cost percent change

- A **+/- 1% pt** deviation in the anticipated air vehicle production rate slope % results in roughly **+/- 5%** change to Canada's URF cost
- A **+/- 1% pt** deviation in the anticipated air vehicle learning curve slope % results in roughly **+/- 7%** change to Canada's URF cost.

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Results: Sensitivity Analysis

What if participants withdraw or cancel?

Scenario A:

Major European partner withdraws

Scenario B:

Two major partners withdraw

Scenario C:

Only U.S. and Canada remain

Scenario D:

U.S. downsizes to 75%, only Canada remains

Scenario E:

U.S. downsizes to 50%, only Canada remains

		Estimated Cost (as a % of the baseline estimate)				
Lot	Year	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E
4	2010	0%	0%	2%	8%	19%
5	2011	0%	0%	0%	7%	17%
6	2012	0%	1%	5%	12%	22%
7	2013	3%	3%	7%	14%	26%
8	2014	2%	3%	10%	18%	29%
9	2015	3%	4%	12%	19%	30%
10	2016	2%	4%	13%	20%	30%
11	2017	2%	4%	13%	20%	30%
12	2018	2%	4%	12%	19%	28%
13	2019	2%	4%	11%	18%	27%
14	2020	2%	4%	10%	17%	26%
15	2021	2%	4%	11%	18%	28%
16	2022	1%	2%	7%	15%	25%
17	2023	1%	2%	6%	13%	24%
18	2024	1%	1%	3%	10%	21%
19	2025	0%	1%	3%	10%	20%
20	2026	0%	1%	3%	10%	20%
21	2027	0%	1%	3%	10%	20%
22	2028	0%	1%	3%	10%	20%
23	2029	0%	1%	2%	9%	20%
24	2030	0%	1%	2%	9%	20%
25	2031	0%	1%	2%	9%	20%
26	2032	0%	1%	2%	9%	20%
27	2033	0%	1%	2%	9%	19%
28	2034	0%	1%	2%	9%	20%
29	2035	0%	1%	2%	9%	19%

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Results: Sensitivity Analysis

- What if participants withdraw or cancel?

Sample Results:

- Major European partner withdraws: **2% increase**
- Two major partners withdraw: **4% increase**
- Only U.S. and Canada remain: **12% increase**
- U.S. downsizes to 75%, only Canada remains: **18% increase**
- U.S. downsizes to 50%, only Canada remains: **28% increase**

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Results: Secondary URF Cost Estimate

- URF Estimates:
  - Baseline estimate 13.5% higher than the JPO estimate.

- Using best-fit quantity effects models to initial LRIP lots
- Secondary, independent estimate.
- Void of any risk or uncertainty considerations and is valid if the program runs without any improvements or hitches, no withdrawals/downsizing/changes to orders, etc.
- Considered complementary to JPO estimate given the cost estimate is top-down and lacks the more detailed granularity of JPO's cost estimate.

Based on limiting assumptions, e.g.:

- **Model is high-level (not at component level like JPOs)**
- **Doesn't consider STOVL or CV numbers & commonality**

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Risk / Uncertainty Analysis

- Daunting task to complete bottom-up
- U.S. JPO yet to formally complete/disclose
  - Grandfather clause exemption to 2009 WSARA law?
  - Will CAPE perform such analysis?
- Canadian DND needed to do this to:
  - Determine/defend appropriate level of contingency
  - Examine worst-case scenarios
  - Give decision-makers appreciation of confidence levels

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Risk / Uncertainty Analysis

- Employed a top-down approach using U.S. Naval Center for Cost Analysis (NCCA) model:

  Flynn, B. and Garvey, P. (2011), Weapon Systems Acquisition Reform Act (WSARA) and the Enhanced Scenario-Based Method (eSBM) for Cost Risk Analysis, Technical Report Naval Center for Cost Analysis, Washington DC.

  - NCCA analyzed historical cost growth factors of 100 major U.S. acquisitions
  - Compared estimates at various milestones to actuals (at completion)
  - Computed expected cost growth factors (CGF)

	Cost Growth Factor	
	MS B	MS C
Mean	1.36	1.10
Standard Deviation	0.69	0.28

  - NCCA's findings consistent with a 2006 RAND study

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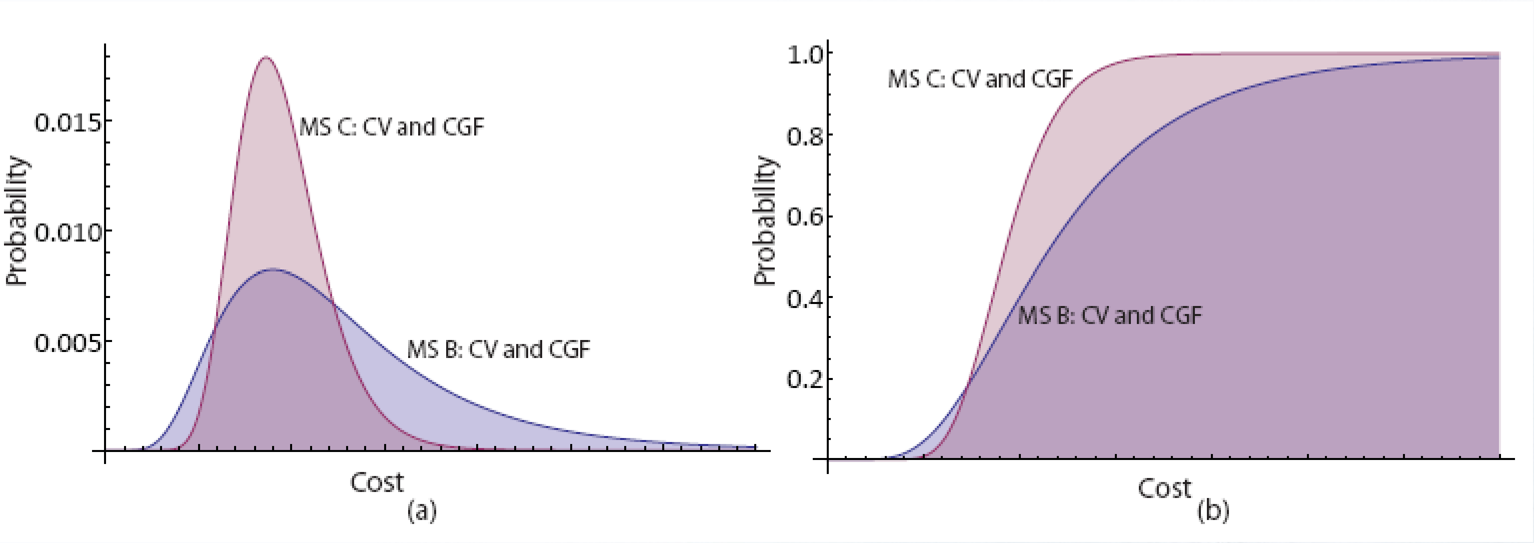
Risk / Uncertainty Analysis

- Applied NCCA model to Canadian avg. URF cost estimate:

	Based on Historical MS B	Based on Historical MS C
Mean	152%	114%
Mode	108%	103%
Median	136%	110%
20th percentile	91%	89%
80th percentile	203%	136%

Risk / Uncertainty Analysis

- Applied NCCA model to Canadian avg. URF cost estimate:



- NCCA's CGF (mean and variance) is used to adjust a baseline estimate to obtain a mean, risk-adjusted, estimate:
  - **Contingency:** 13.5% contingency for 55% confidence
  - **Worst-case planning:** 36% cost overrun (20% chance)

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Risk / Uncertainty Analysis

- Applied NCCA model to Canadian avg. URF cost estimate:

Percentile	Change in Cost	Percentile	Change in Cost
5th	-27%	55th	14%
10th	-20%	60th	17%
15th	-15%	65th	21%
20th	-11%	70th	26%
25th	-7%	75th	30%
30th	-4%	80th	36%
35th	0%	85th	43%
40th	3%	90th	52%
45th	7%	95th	66%
50th	10%		

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Risk / Uncertainty Analysis

- "Worst-case": 20% chance of 36% overrun

- <u>Example</u>:
  - production rate efficiencies are not realized (a 5% increase in the predicted production rate slope percentage)

combined with

  - the withdrawal of two major international partners.

- Validation: 20% chance of this or worse happening reasonable?

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Recommendations

- International JSF Partners decision makers should consider the risk, uncertainty, and sensitivity analyses presented herein to determine an appropriate level of budget contingency - and be aware of the associated confidence level.
- International JSF Partners should use the presented quantity effect model to update the cost estimates as additional LRIP data and production profiles are made available by the U.S. JPO.
- International JSF Partners should develop and explore other worst-case risk and uncertainty scenarios: e.g., model inflation/exchange rates
- DRDC CORA prepared a self-contained report (scientific peer-review) documenting the methods and estimates
- Recommend collaboration amongst partners in F-35 cost modelling
  - E.g., scientific and/or cost analysts collaboration / conferences.

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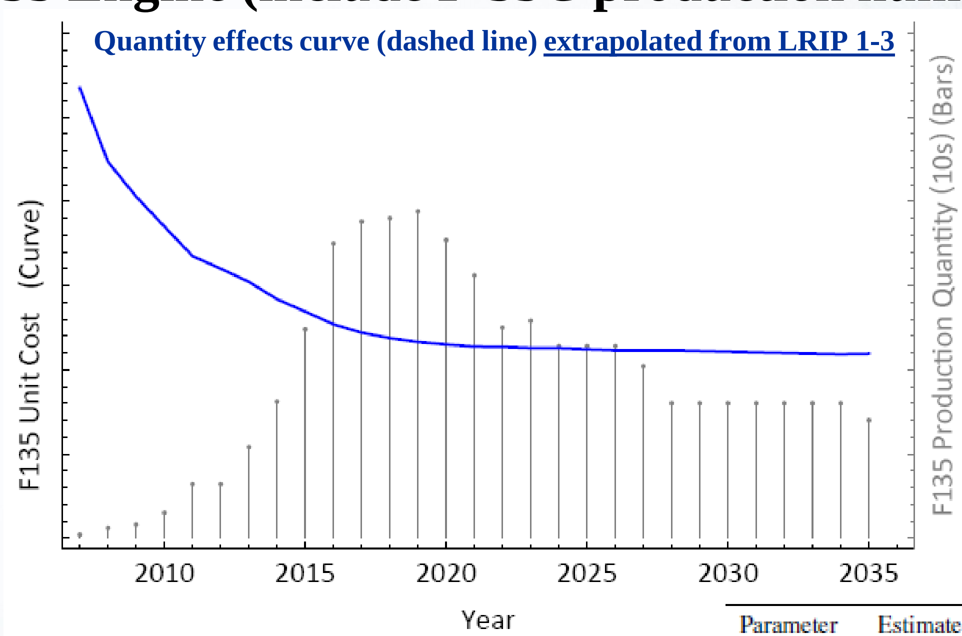
Application to F-35A: F135 Engine

- Given LRIPs 1-3, project future costs:

INPUT:	JPO Predictions (29yrs)	Actual Completed LRIP Costs
OUTPUT:	Reverse engineered learning slope %s	- Year-by-year projections - Learning slope %s

F135 Engine (include F-35C production numbers)



RAND Historical
PR Slope% = 97%

Estimated:
CI Slope % = 93%

Parameter	Estimate	Standard Error	95% Confidence Interval	*t*-Statistic	*P*-Value
T_1	28.4	1.02	(15.5, 41.3)	27.9	0.023
CI Slope %	0.93	0.02	(0.74, 1.13)	60.8	0.010

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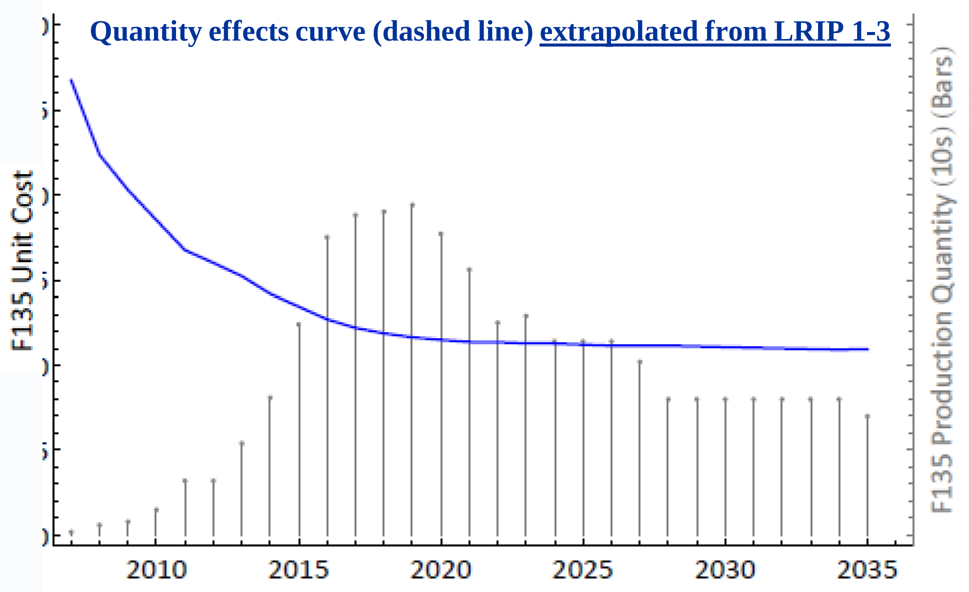
Application to F-35A: F135 Engine

- Given LRIPs 1-3, project future costs:

F135 Engine (include F-35C production numbers)



Lot	Qty
LRIP 1	2
LRIP 2	6
LRIP 3	8

RAND Historical
PR Slope% = 97%
Estimated:
CI Slope % = 93%

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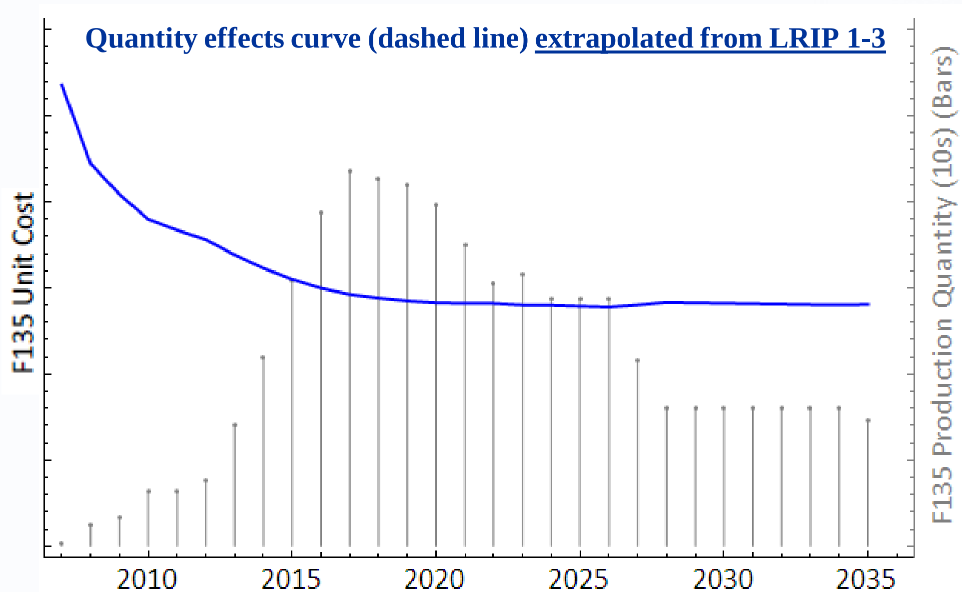
Application to F-35A: F135 Engine

- Given LRIPs 1-3, project future costs:

F135 Engine (include F-35C and F-35B production numbers)



Lot	Qty
LRIP 1	2
LRIP 2	12
LRIP 3	17

RAND Historical
PR Slope% = 97%
Estimated:
CI Slope % = 96%

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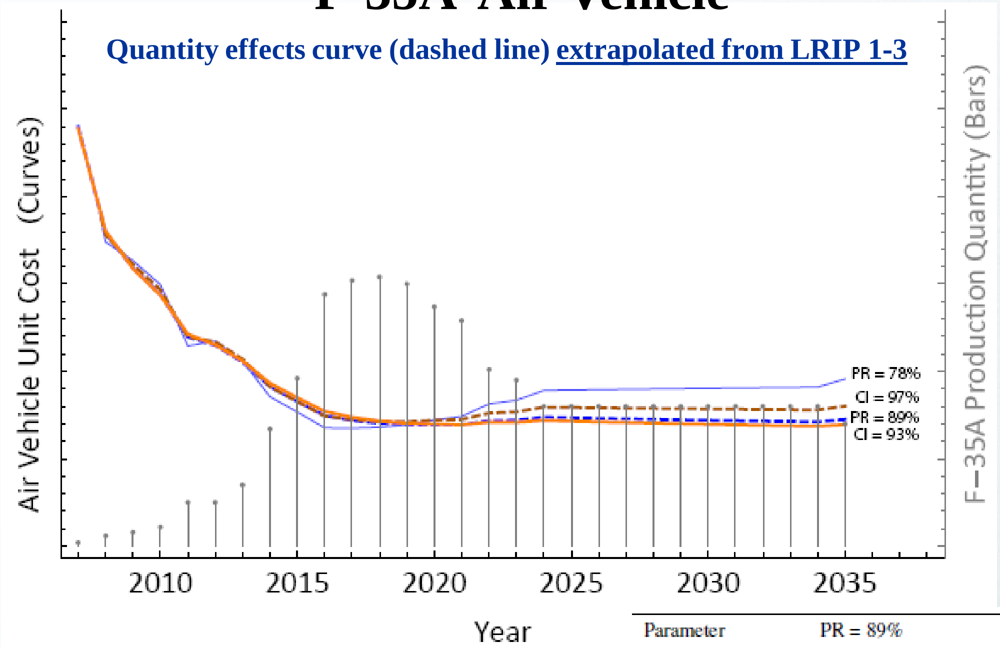
Application to F-35A: Air Vehicle

- Given LRIPs 1-3, project future costs:

INPUT:	JPO Predictions (29yrs) ↓	Actual Completed LRIP Costs ↓
OUTPUT:	Reverse engineered learning slope %s	- Year-by-year projections - Learning slope %s

F-35A Air Vehicle



Chosen Model

RAND Historical

PR Slope% = 89%

Estimated:

CI Slope % = 95%

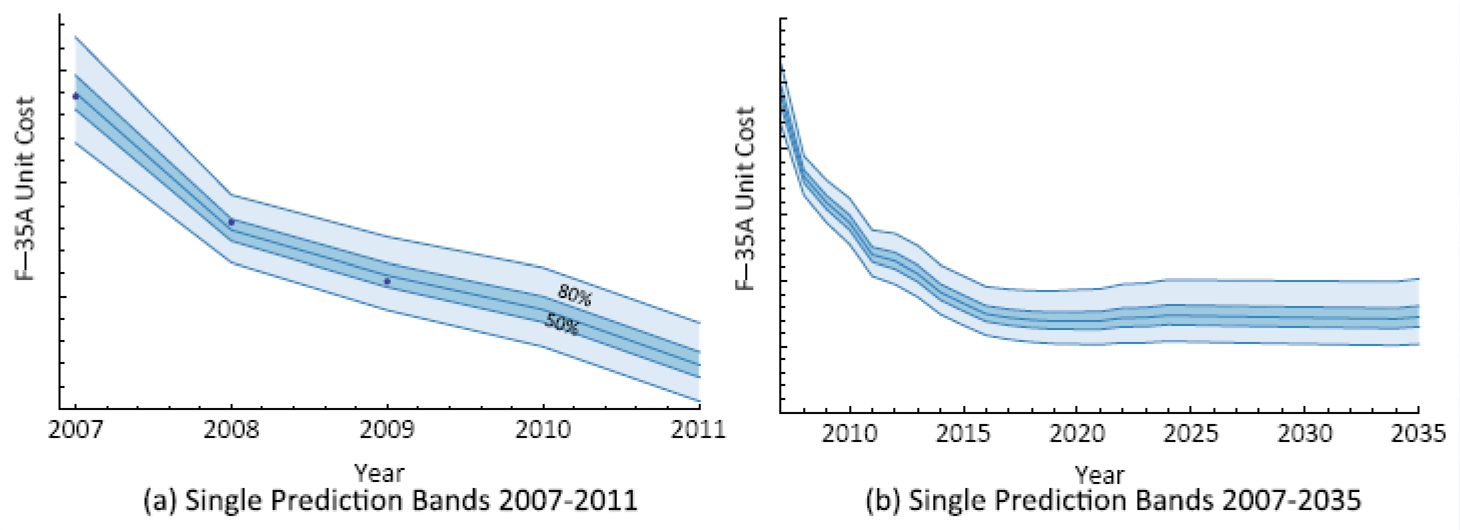
Parameter	PR = 89%	PR = 78%	CI = 97%	CI = 93%
T_1	276.5, 7.4, (182.8, 370.1)	306.3, 20.9, (40.0, 572.5)	282.1, 15.2, (88.3, 475.8)	269.8, 7.2, (178.7, 360.8)
PR slope %	0.89	0.78	0.86, 0.02, (0.60, 1.12)	0.91, 0.01, (0.78, 1.05)
CI Slope %	0.95, 0.01, (0.81, 1.08)	1.03, 0.03, (0.65, 1.42)	1.03	0.93

DEFENCE DÉFENSE

Application to F-35A: Air Vehicle

- Given LRIPs 1-3, project future costs:

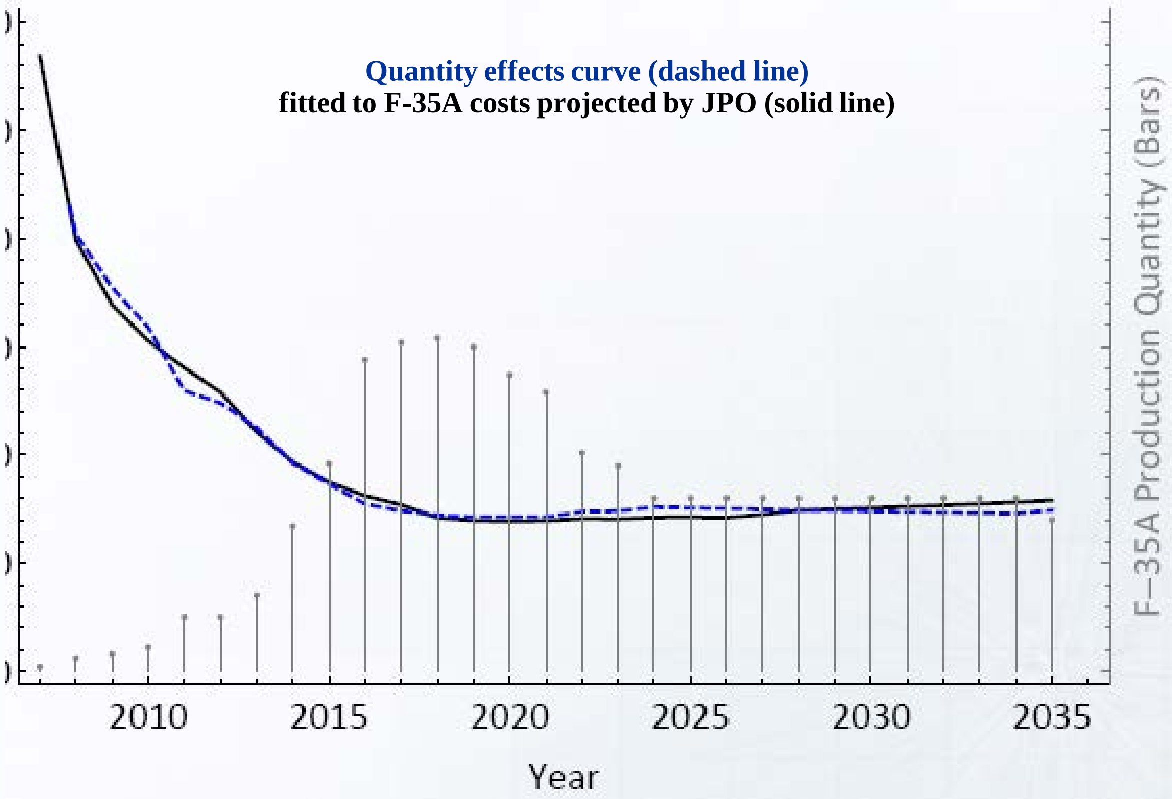
INPUT:	JPO Predictions (29yrs) ↓	Actual Completed LRIP Costs ↓
OUTPUT:	Reverse engineered learning slope %s	- Year-by-year projections - Learning slope %s



Single prediction bands of the F-35A air vehicle quantity effects regression model: (a) 2007 to 2011 (b) 2007-2035

Application to F-35A

- Reverse engineered JPO Predictions (06/11):



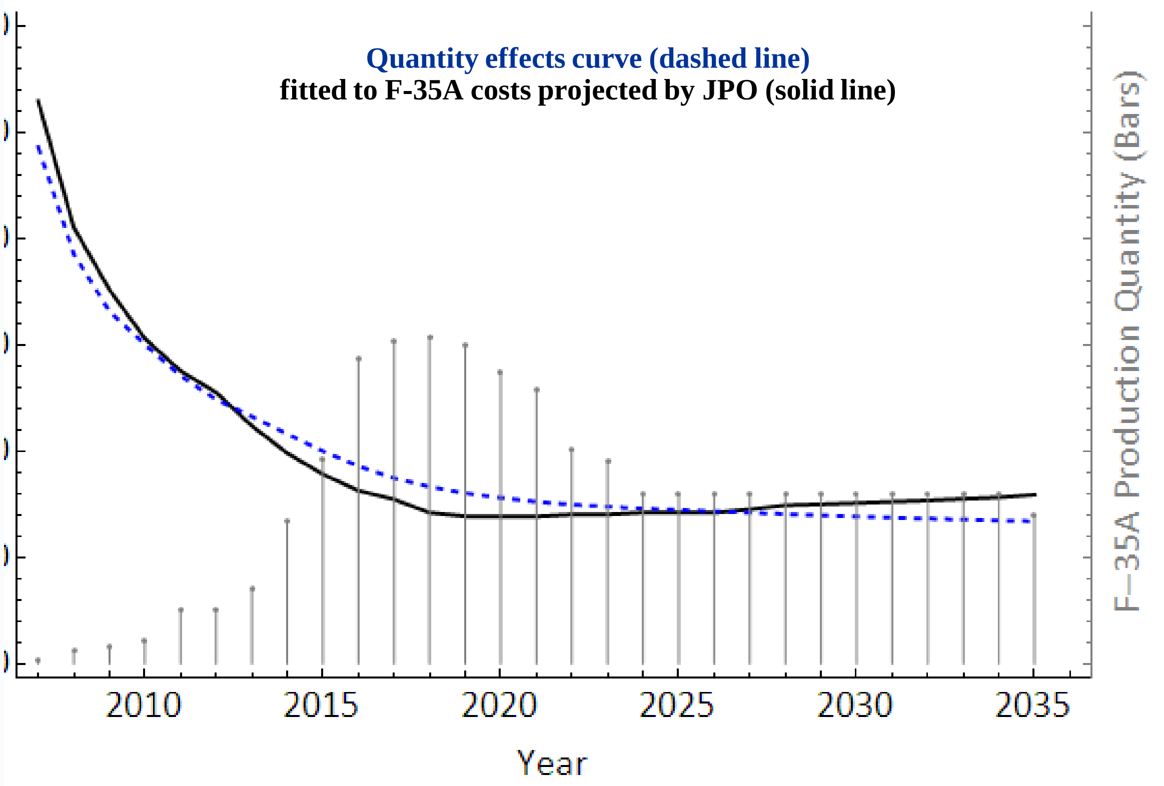
CI slope = 94%
PR slope = 89%

R^2 = 0.9999

DEFENCE DÉFENSE

Application to F-35A

- Reverse engineered JPO Predictions (06/11):

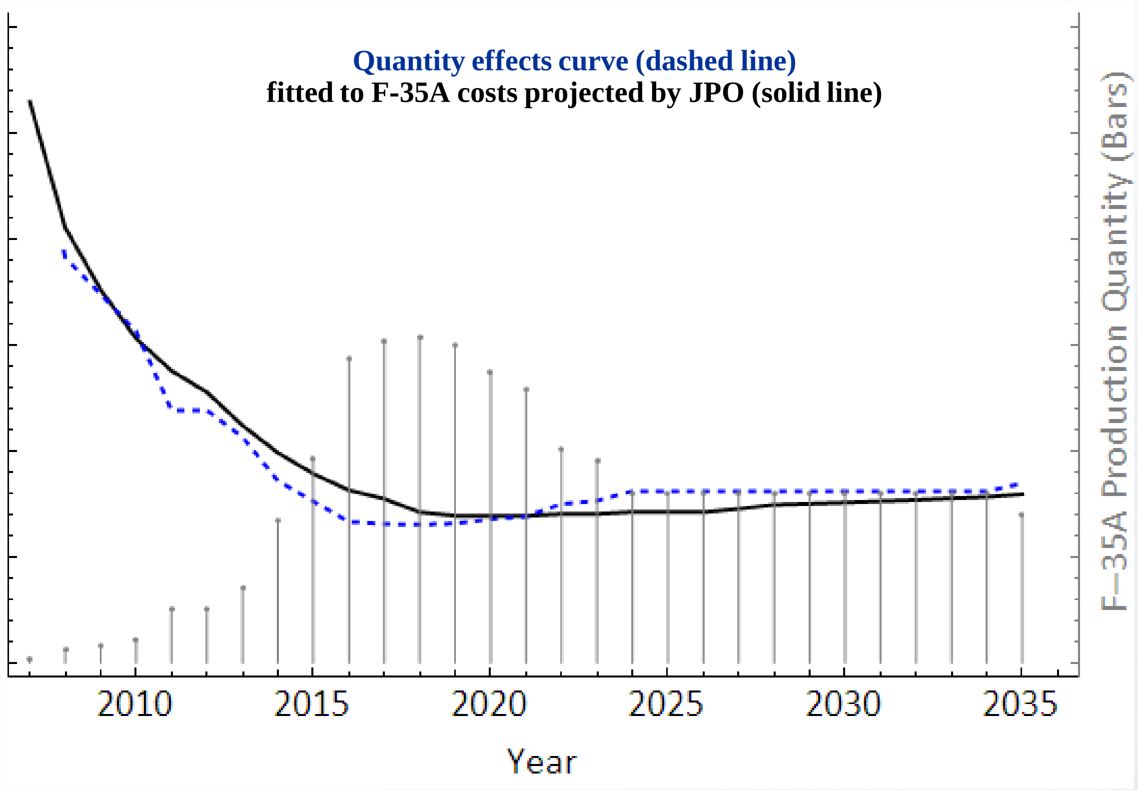


CI slope = 89%
PR slope = 100%

R^2 = 0.9995

Application to F-35A

- Reverse engineered JPO Predictions (06/11):



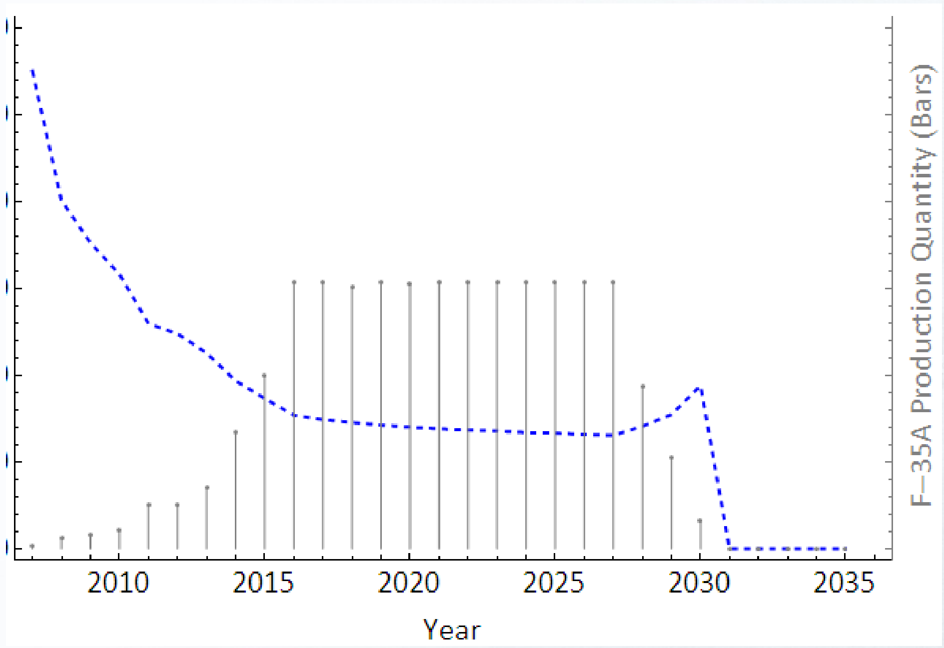
CI slope = 100%
PR slope = 79%

$R^2 = 0.9995$

DEFENCE DÉFENSE

Optimized F-35A Production Plan?

- $180B program cost (for all URF)
  - Assume best-fit CI and PR %s.
  - Can optimize to determine best production plan



  - One example saves $7B total: lower URF costs during peak