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# Developing a Military Aircraft Cost Estimating Model in Korea

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# Introduction

- Background
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# Background



- **Emphasis on cost analysis to obtain efficiency & effectiveness in weapon system acquisition process in Korea**
  - **Cost analysis result is a critical factor in decision making now**
- **Infrastructure of cost analysis is weak**
  - **Methodologies**
  - **Tools / Data Base**
  - **Currently using overseas cost estimation models (PRICE, SEER, etc)**
- **Limited in historical data to develop own cost estimation models & to calibrate existing cost estimation models**
  - **Commercial cost models do not fit to the Korean defense industry environment**

Need the Korean version cost estimation model suitable for the Korean defense industry environment

# History



## Preliminary research for cost analysis model (2009)

- Development Requirement
- Possibility analysis & development outline

## Conceptual study on the cost model (2010)

- Develop cost estimation logic in various cases
- Construct system development plan
  - Verification for result : ADD, MCR

## The first pilot model development for missile system (2011)

- Historical data collection
- Define WBS & cost driver
- Verify the model with historical data
  - Verification for result : ADD, MCR

## The second pilot model for military aircraft (2012)

- Historical data are limited
- Need calibration using foreign data when developing CER
  - Verification for result : ADD, MCR(Joint study)

# Model Development Framework



## Model development framework

- **Model consists of many CERs**
- **CERs should estimate life-cycle cost**
  - **R&D, production, O&S for HW based on the Korean defense industry cost accounting system**
  - **R&D, O&S for SW based on the Korean regulation of SW cost estimation**
- **CERs will be developed on the basis of 8 categories in the Korean standard classification of weapon system**

# Model Development Process



## Definition of model development process

- Define **seven** development steps
  - Apply process and methodologies developed in the **Conceptual Study**(2010)
    - * Model development process in the conceptual study was developed on the basis of **general model development process**

**General Model Development Process**

1. Parametric Estimating Handbook(2007)
2. USA Boeing Company
3. COCOMO 2(Boehm)
4. Defense SW Cost Estimation Model(KAIST)

**Conceptual Study**

1. Opportunity Identification
2. Definition of the model
3. Data collection & analysis
4. Model development
5. Validation & Verification
6. Operation & Maintenance

**The Model Development Process for Missile System**

1. Analysis for the System
2. WBS Definition
3. Cost Drivers Identification
4. Data Collection & Analysis
5. CER Development
6. Cost Factor Identification
7. Cost Integration & Validation

# R&D Cost Estimation Model

- Analysis for the Military Aircraft
- WBS Definition
- Cost Drivers Identification
- Data Collection & Analysis
- CER Development
- Cost Factor Identification
- Cost Integration & Verification

# 1. Analysis for the Aircraft System



## A. Definition

The complex of equipment (hardware/software), data, services and facilities required to develop and produce air vehicles

## B. Main structure

- Air Vehicle
  : Airframe, Propulsion,
  Air Flight Control System, etc.
- Avionics
  : Radar, Communication,
  Navigation & Guidance, etc.
- Weapon system
  : Pylon, Gun, Rocket, Missile, etc.

## C. The scope of military aircraft

- Fighter - Attacker
- Controller - Trainer

# 2. WBS Definition



## A. WBS for R&D

- **1. Aircraft System**
  - **1.1 Air Vehicle**
    - 1.1.1 Airframe Structure
    - 1.1.2 Propulsion System
    - 1.1.3 Air Flight Control System
    - 1.1.4 Avionics System
    - 1.1.5 Weapon System
  - 1.2 I&T
  - 1.3 SE/PM
  - 1.4 T&E
  - 1.5 Tool & Equipment
  - 1.6 Data
  - 1.7 Training
  - 1.8. ILS
  - 1.9 Technology Transfer
  - 1.10 Military Facility
  - 1.11 Other

# 3. Cost Drivers Identification



## A. Identify all Feasible Cost Drivers

| Type | | Type | |
|---|---|---|---|
| **Control** | Pilot number | **Climb** | Service Ceiling(ft or km) |
| **Airframe** | Length(m of ft) | | Maximum rate of climb(m/s or ft/min) |
| | Span(m of ft) | | Circling Flight Capacity |
| | Height(m of ft) | **Engine** | Max. Engine Thrust(lbs) |
| | Radar Cross Section(RCS)(ft2 or m2) | | Thrust to weight Ratio |
| | G-Limit(g) | | Engine number |
| | Design Fatigue Life(Hour) | | Engine Type |
| **Weight** | Empty Weight(lb or kg) | | Engine Name |
| | Max Takeoff Weight(lb or kg) | **Fuel** | Max. Fuel capacity |
| | Empty Weight by WBS(lb or kg) | | Fuel Consumption |
| **Speed** | Max Speed(km/h or Mach) | | Endurance Hour(Hour) |
| | Cruising speed(km/h) | **Generator** | Generator Power(kw) |
| **Range** | Ferry Range (with -)(km or nmi) | | Battery Capacity |
| | Ferry Range (Without -)(km or nmi) | **Hydraulics** | Hydraulics Pressure(psi) |
| | Max Range(ft or km) | **Weapon** | Pylon number |
| | Combat Radius(ft or km) | | Weapon type(Gun, Missile, Bomb) |
| | Takeoff Distance(ft or m) | **Others** | Thrust Specific Fuel Consumption, |
| | Landing Distance(ft or m) | | The type of aircraft(trainer, attacker, fighter) |

- Some cost drivers are eliminated among all feasible cost drivers considering security, the relationship of R&D cost, the possibility of data collection in earlier phase of acquisition

# 3. Cost Drivers Identification (Cont')



## B. Identify Main Cost Drivers

| Characteristic Variables(12) | Dummy Variables(4) |
|---|---|
| Length(m of ft), Span(m of ft), Height(m of ft), Empty Weight(lb or kg), Max Takeoff Weight(lb or kg), Max Speed(km/h or Mach), Max Range(ft or km), Combat Radius(ft or km), Service Ceiling(ft or km), G-Limit(g), Max. Engine Thrust(lbs), Max. Fuel capacity, | The type of aircraft (Trainer, Attacker, Fighter)<br>The type of engine (Turboprop, Turbofan),<br>The number of pilot (One, Two)<br>The number of engine (One, Two) |

- Some main cost drivers are eliminated among Main Cost Drivers considering the similarity of characteristic

  Ex) Length / Span / Height, Empty Weight / Max Takeoff Weight

## C. The final Cost Drivers

| Characteristic Variables(9) | Dummy Variables(4) |
|---|---|
| Span(m of ft), Empty Weight(lb or kg), Max Speed(km/h or Mach), Max Range(ft or km), Combat Radius(ft or km), Service Ceiling(ft or km), G-Limit(g), Max. Engine Thrust(lbs), Max. Fuel capacity | The type of aircraft (Trainer, Attacker, Fighter)<br>The type of engine (Turboprop, Turbofan),<br>The number of pilot (One, Two)<br>The number of engine (One, Two) |

# 4. Data collection & Analysis



## A. Military Aircraft List to collect the data

1. ROK data

| KT-1 | KA-1 | T-50 |
|---|---|---|
| Basic Trainer | Forward Air Controller | Advanced Trainer |
|  |  |  |
| For R&D and Production | For Production | For R&D and Production |

# 4. Data collection & Analysis (Cont')



## A. Military Aircraft List to collect the data (Cont')

2. USA data

| A-10(Attacker) | F-15(Fighter) | F-16(Fighter) |
|---|---|---|
| | | |

| F-18(Fighter) | F-22(Fighter) | F-35(Fighter) |
|---|---|---|
| |  |  |

# 4. Data collection & Analysis (Cont')



## B. Cost Drivers Data Collection & Analysis

| Type | KT-1 | KA-1 | T-50 | A-10 | F-15E | F-16C/D | F-18E | F-22 | F-35A |
|---|---|---|---|---|---|---|---|---|---|
| **The type of aircraft** | Trainer | Controller | Trainer | Attacker | Fighter | Fighter | Fighter | Fighter | Fighter |
| **The number of pilot** | | | | | | | | | |
| **Span(m)** | | | | | | | | | |
| **G-limit(g)** | | | | | | | | | |
| **Empty Weight(lb)** | | | | | | | | | |
| **Max. Speed(km/h)** | | | | | | | | | |
| **Max. Range(km)** | | | | | | | | | |
| **Combat Range(km)** | | | | | | | | | |
| **Service Ceiling(km)** | | | | | | | | | |
| **Engine Thrust(lbs)** | | | | | | | | | |
| **The number of Engine** | | | | | | | | | |
| **The type of Engine** | | | | | | | | | |
| **Max. Fuel Capacity(kg)** | | | | | | | | | |
| **The number of Prod.** | | | | | | | | | |
| **Learning Rate** | | | | | | | | | |

# 4. Data collection & Analysis (Cont')



## C. R&D Cost Data Collection & Analysis

| ※ R&D Cost by WBS | KT-1 | T-50(FA-50) | A-10 | F-15C/D | F-16C/D | F-18E/F | F-22 | F-35A |
|---|---|---|---|---|---|---|---|---|
| 1. Aircraft | | | | | | | | |
| 1.1 Air Vehicle | | | | | | | | |
| 1.1.1 Airframe | | | | | | | | |
| 1.1.2 Propulsion | | | | | | | | |
| 1.1.3 Air Flight Control System | | | | | | | | |
| 1.1.4 Avionics | | | | | | | | |
| 1.1.5 Weapon System | | | | | | | | |
| 1.2 SE/PM | | | | | | | | |
| 1.3 System Integration | | | | | | | | |
| 1.4 T&E | | | | | | | | |
| 1.5 Tool & Equipment | | | | | | | | |
| 1.6 Data | | | | | | | | |
| 1.7 Training | | | | | | | | |
| 1.8 ILS | | | | | | | | |
| 1.9 Technology Transfer | | | | | | | | |
| 1.10 Military Facility | | | | | | | | |
| 1.11 Other | | | | | | | | |

Korea Won(Unit) : 100M ₩

US dollar(Unit) : 1M $

# 4. Data collection & Analysis (Cont')



## D. Calibration from USA dollar($) to Korea Won(₩)

- Main Calibration Factors

- Hourly(Monthly, Yearly) Labor Compensation Costs in Manufacturing

  * Hourly Labor Compensation Costs (2012 year) : USA($36.71), ROK($18.49)

- The average of Yearly Labor Hours in Manufacturing

  * The average of Yearly Labor Hours (2010 year) : USA(1,695 h), ROK(2,193 h)

- Labor Productivity in Manufacturing

  * Labor Productivity in Manufacturing (2012 year) : USA($119,660), ROK($104,000)

➡ These factors effect only labor cost

➡ So we supposed that Material and Others costs are same in USA and ROK,

their cost effect only the exchange rate between USA and ROK

# 4. Data collection & Analysis (Cont')



## D. Calibration from USA dollar($) to Korea Won(₩) (Cont')

- Calibration Logic

$$\text{R\&D,Production Cost(ROK Won)} = [\ \text{Material cost(\$)} + \text{Others cost(\$)} + \text{Labor cost(\$)} \times \frac{\text{Compensation rate} \times \text{Labor Hours rate}}{\text{Labor Productivity rate}}\ ] \times \text{Exchange Rate(Won)}$$

$$* \text{ Compensation Rate} = \frac{\text{ROK Hourly Compensation cost in mannufacturing}}{\text{USA Hourly Compensation cost in mannufacturing}} = \frac{\$18.49}{\$36.71} = 0.5037\text{(2012 year)}$$

* Bureau of Labor Statistics U.S. Department of Labor, "International Comparisons of Hourly Compensation Costs in Manufacturing 2010",

$$* \text{ Labor Hours Rate} = \frac{\text{ROK Yearly Labor Hours in mannufacturing}}{\text{USA Yearly Labor Hours in mannufacturing}} = \frac{2{,}193\text{h}}{1{,}695\text{h}} = 1.2938\text{(2010 year)}$$

$$* \text{ Labor Productivity Rate} = \frac{\text{ROK Labor Productivity in mannufacturing}}{\text{USA Labor Productivity in mannufacturing}} = \frac{\$104{,}000}{\$119{,}660} = 0.74984\text{(2012 year)}$$

* Korea Productivity Center, The cross-national Comparison of Productivity, Dec. 2011"

* Exchange Rate = 1,126 Won per $1

(The average of exchange rates of Jan., Feb, Mar., and Apr. 2012)

# 4. Data collection & Analysis (Cont')



## E. The Calibrated Cost Data

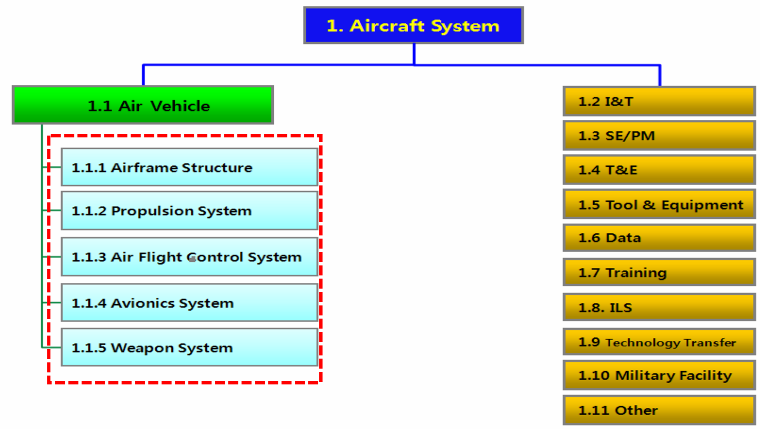
| ※ R&D Cost by WBS | KT-1 | T-50(FA-50) | A-10 | F-15C/D | F-16C/D | F-18E/F | F-22 | F-35A |
|---|---|---|---|---|---|---|---|---|
| 1. Aircraft | ₩1,845.88 | ₩28,685.80 | ₩70,939.20 | ₩56,535.75 | ₩40,497.75 | ₩83,652.54 | ₩442,781.12 | ₩655,156.49 |
| 1.1 Air Vehicle | ₩988.94 | ₩15,368.47 | ₩38,127.66 | ₩30,542.18 | ₩21,766.30 | ₩44,554.94 | ₩237,518.62 | ₩351,441.96 |
| 1.1.1 Airframe | ₩472.61 | ₩7,344.57 | ₩13,163.46 | ₩17,305.45 | ₩7,514.75 | ₩21,577.25 | ₩118,822.85 | ₩175,814.99 |
| 1.1.2 Propulsion | ₩166.63 | ₩2,589.55 | ₩7,413.95 | ₩3,884.60 | ₩4,232.47 | ₩12,598.14 | ₩33,911.57 | ₩50,176.90 |
| 1.1.3 Air Flight Control System | ₩184.92 | ₩2,873.69 | ₩10,096.49 | ₩5,523.32 | ₩5,763.88 | ₩2,007.38 | ₩47,196.03 | ₩69,833.12 |
| 1.1.4 Avionics | ₩105.17 | ₩1,634.44 | ₩6,026.80 | ₩1,596.75 | ₩3,440.58 | ₩4,502.65 | ₩23,471.14 | ₩34,728.83 |
| 1.1.5 Weapon System | ₩59.60 | ₩926.22 | ₩1,426.96 | ₩2,232.07 | ₩814.62 | ₩3,869.53 | ₩14,117.04 | ₩20,888.12 |
| 1.2 SE/PM | ₩144.91 | ₩2,252.02 | ₩5,359.62 | ₩4,003.19 | ₩3,059.71 | ₩7,018.04 | ₩34,249.10 | ₩50,676.32 |
| 1.3 System Integration | ₩158.23 | ₩2,458.96 | ₩6,100.43 | ₩4,886.75 | ₩3,482.61 | ₩7,128.79 | ₩38,002.98 | ₩56,230.71 |
| 1.4 T&E | ₩227.46 | ₩3,534.75 | ₩8,769.36 | ₩7,024.70 | ₩5,006.25 | ₩10,247.64 | ₩54,629.28 | ₩80,831.65 |
| 1.5 Tool & Equipment | ₩118.67 | ₩1,844.22 | ₩4,575.32 | ₩3,665.06 | ₩2,611.96 | ₩5,346.59 | ₩28,502.23 | ₩42,173.03 |
| 1.6 Data | ₩19.78 | ₩307.37 | ₩762.55 | ₩610.84 | ₩435.33 | ₩891.10 | ₩4,750.37 | ₩7,028.84 |
| 1.7 Training | ₩98.89 | ₩1,536.85 | ₩3,812.77 | ₩3,054.22 | ₩2,176.63 | ₩4,455.49 | ₩23,751.86 | ₩35,144.20 |
| 1.8 ILS | ₩89.00 | ₩1,383.16 | ₩3,431.49 | ₩2,748.80 | ₩1,958.97 | ₩4,009.94 | ₩21,376.68 | ₩31,629.78 |
| 1.9 Technology Transfer | | | | | | | | |
| 1.10 Military Facility | | | | | | | | |
| 1.11 Other | | | | | | | | |

# 5. CER Development



## A. R&D CER Development

1. The scope of CER development




2. Data used for R&D CER development(7)

   - T-50 (ROK) / A-10, F-15E, F-16C/D, F-18E, F-22, F-35A(USA)

     * KT-1 data is outlier as a result of previous analysis

       (Reason) The difference of R&D cost is so high : T-50(15 times), F-35A(350 times)

       The difference of mission and engine type

       : KT-1(Trainer, Turboprop), The others(Attacker and Fighter, Turbofan)

3. Criteria for CER selection

   - p-value ≤ 0.1 and $R^2_{adj}$ ≥ 0.8
   - $MMRE = \frac{1}{n}\sum_{i=1}^{n}\frac{|y_i - \hat{y}_i|}{y_i}$ ≤ 0.25
   - $PRED(l) = \frac{L}{n}$ ≥ 0.75
   - $RMSE = \sqrt{\frac{1}{n-k-1}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$

# 5. CER Development



## B. CER Development  Methodology

- Apply various regression methods according to collected data characteristics to increase the accuracy of  CERs

* Considered data characteristics

  a. Multicollinearity

  b. Outlier

  c. Heteroscedasticity

* Considered regression method

  a. Multiple linear regression

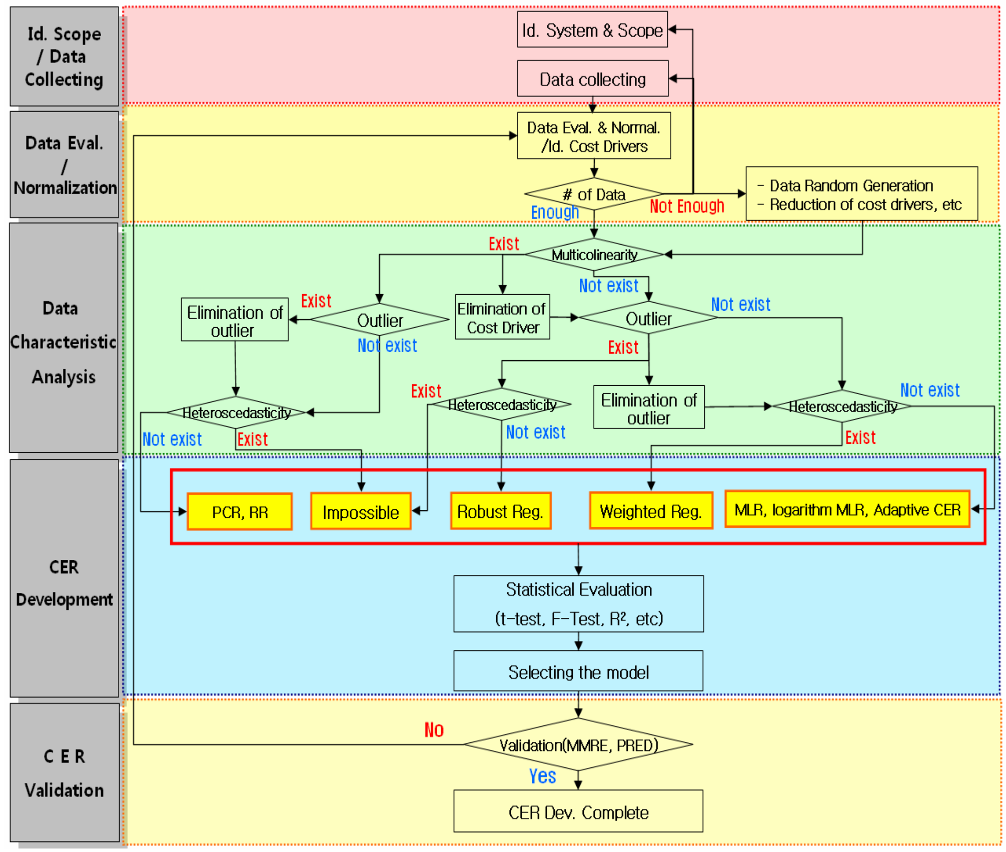
  b. Log multiple linear regression

  c. Robust regression

  d. Principle component regression

  e. Ridge regression

  f.  Weighted regression



# 5. CER Development (Cont')



## C. Developed R&D CER

### 1. Airframe Structure

$$\text{Airframe R\&D cost} = -2245101 + 325228\times(\ln(\text{Empty Weight})) - 92748\times(\ln(\text{Thrust})) + 26.3\times(\text{Max. Speed}) - 145082\times(\text{No. Engine}^{*})$$

*** Correlation of Empty weight and Thrust(0.652)** **(Empty Weight = 0.31*(Thrust) + 13655)**

*** $R^2_{adj}$ = 0.998, MMRE = 0.0616, RMSE = 2961, PRED(0.25) = 1**

### 2. Propulsion System

$$\text{Propulsion R\&D cost} = -615080 + 83666\times(\ln(\text{Empty Weight})) - 18647\times(\ln(\text{Thrust})) - 6993\times(\text{Attacker}^{*}) - 34784\times(\text{No. Engine}^{*})$$

*** Correlation of Empty weight and Thrust(0.652)** **(Empty Weight = 0.31*(Thrust) + 13655)**

*** $R^2_{adj}$ = 0.998, MMRE = 0.0522, RMSE = 840, PRED(0.25) = 1**

# 5. CER Development (Cont')



## C. Developed R&D CER (Cont')

### 3. Air Flight Control System

$$\text{Air Flight R\&D cost} = -1198052 + 117922\times(\ln(\text{Empty Weight})) + 11967\times(\ln(\text{Combat Range})) - 33023\times(\text{Fighter}^{*}) - 59396\times(\text{No. Engine}^{*})$$

*** $R^2_{adj}$ = 0.999, MMRE = 0.0692, RMSE = 579, PRED(0.25) = 0.86**

### 4. Avionics System

$$\text{Avionics R\&D cost} = -480297 + 57597\times(\ln(\text{Empty Weight})) - 11212\times(\ln(\text{Thrust})) + 5187\times(\ln(\text{Max. Range})) - 30291\times(\text{No. Engine}^{*})$$

*** Correlation of Empty weight and Thrust(0.652) (Empty Weight = 0.31*(Thrust) + 13655)**

*** $R^2_{adj}$ = 0.998, MMRE = 0.055, RMSE = 341, PRED(0.25) = 1**

### 5. Weapon System

$$\text{Weapon System R\&D cost} = -292636 + 37494\times(\ln(\text{Empty Weight})) - 10414\times(\ln(\text{Thrust})) + 4906\times(\ln(\text{Max. Speed})) - 15740\times(\text{No. Engine}^{*})$$

*** Correlation of Empty weight and Thrust(0.652) (Empty Weight = 0.31*(Thrust) + 13655)**

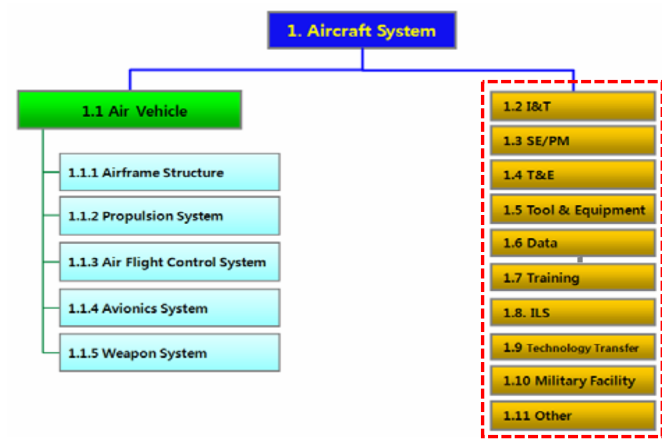
*** $R^2_{adj}$ = 0.998, MMRE = 0.072, RMSE = 397, PRED(0.25) = 1**

# 6. Factor Estimation Relationship(FER)



## A. R&D FER Development

1. The scope of FER development




2. Cost Factors Ratio

- ROK : Missile cost Estimation Model in previous study
- USA : USA FAA Cost Factor Ratio
- The differences of ROK and USA are so big.
- So we applied ROK cases mostly.

| 구분 | ROK | | | USA | | |
|---|---|---|---|---|---|---|
| | Min | Ave | Max | Min | Ave | Max |
| 1.2 I&T | 0.07 | 0.12 | 0.25 | 0.41 | 0.76 | 1.10 |
| 1.3 SE/PM | 0.02 | 0.06 | 0.13 | | | |
| 1.4 T&E | 0.16 | 0.23 | 0.57 | 0.058 | 0.15 | 0.27 |
| 1.5 Tool & Equipment | 0.06 | 0.12 | 0.33 | 0.03 | 0.18 | 0.45 |
| 1.6 Data | 0.01 | 0.02 | 0.05 | 0.01 | 0.21 | 0.27 |
| 1.7 Training | - | - | - | 0.01 | 0.10 | 0.17 |
| 1.8 ILS | 0.03 | 0.09 | 0.23 | 0.01 | 0.19 | 0.39 |

# 7. Integration & Verification



## A. Integration

| WBS | | | Cost Estimation Logics |
|---|---|---|---|
| Aircraft | Air Vehicle | Airframe | $WC_1 = -2245101 + 325228 \times (\ln(\text{Empty Weight})) - 92748 \times (\ln(\text{Thrust})) + 26.3 \times (\text{Max. Speed}) - 145082 \times (\text{No. Engine}^*)$ |
| | | Propulsion | $WC_2 = -615080 + 83666 \times (\ln(\text{Empty Weight})) - 18647 \times (\ln(\text{Thrust}) - 6993 \times (\text{Attacker}^*) - 34784 \times (\text{No. Engine}^*)$ |
| | | AFCS | $WC_3 = -1198052 + 117922 \times (\ln(\text{Empty Weight})) + 11967 \times (\ln(\text{Combat Range})) - 33023 \times (\text{Fighter}^*) - 59396 \times (\text{No. Engine}^*)$ |
| | | Avionics | $WC_4 = -480297 + 57597 \times (\ln(\text{Empty Weight})) - 11212 \times (\ln(\text{Thrust})) + 5187 \times (\ln(\text{Max. Range})) - 30291 \times (\text{No. Engine}^*)$ |
| | | Weapon | $WC_5 = -292636 + 37494 \times (\ln(\text{Empty Weight})) - 10414 \times (\ln(\text{Thrust})) + 4906 \times (\ln(\text{Max. Speed})) - 15740 \times (\text{No. Engine}^*)$ |
| | I&T | | $WC_6 = 0.12 \times (\sum_{i=1}^{5} WC_i)$ |
| | SE/PM | | $WC_7 = 0.06 \times (\sum_{i=1}^{5} WC_i)$ |
| | T&E | | $WC_8 = 0.23 \times (\sum_{i=1}^{5} WC_i)$ |
| | Tool&Equip. | | $WC_9 = 0.12 \times (\sum_{i=1}^{5} WC_i)$ |
| | Data | | $WC_{10} = 0.02 \times (\sum_{i=1}^{5} WC_i)$ |
| | Training | | $WC_{11} = 0.10 \times (\sum_{i=1}^{5} WC_i)$ |
| | ILS | | $WC_{12} = 0.09 \times (\sum_{i=1}^{5} WC_i)$ |
| | Technology Transfer | | Throughput |
| | Military Facility | | Throughput |
| | Other | | Throughput |

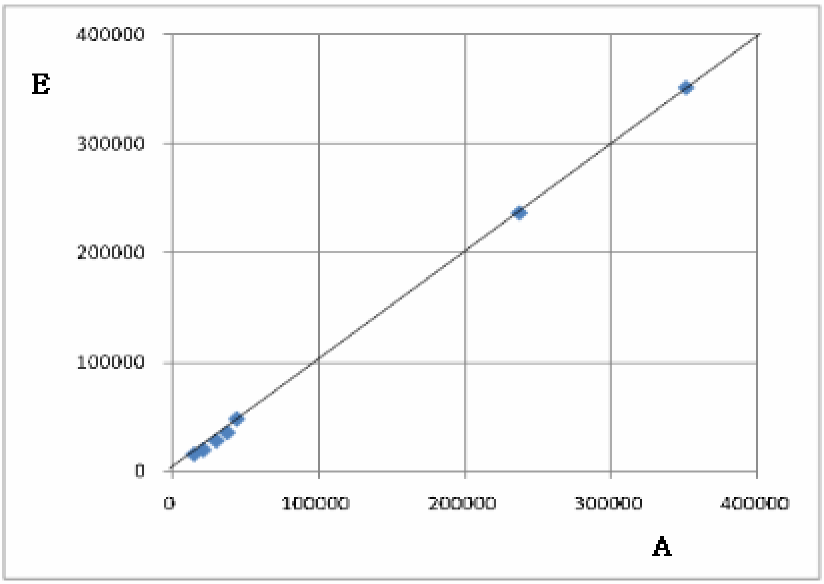
# 7. Integration & Verification (Cont')



## B. Verification

- MMRE and the Comparison of estimated and actual
- Compared actual and estimated only by CER elements (Air vehicle)

| | Actual (A) | Estimated (E) | MRE |
|---|---|---|---|
| T-50 | 15369 | 16524 | 0.0752 |
| A-10 | 38127 | 36364 | 0.0462 |
| F-15E | 30542 | 28770 | 0.0580 |
| F-16C/D | 21767 | 20638 | 0.0519 |
| F-18E | 44555 | 48802 | 0.0953 |
| F-22 | 237519 | 237073 | 0.0019 |
| F-35A | 351442 | 351603 | 0.0005 |
| MMRE = 0.047 | | | |




The developed model can be applicable in earlier phases of acquisition because relative error is lower than 5%

# Production Cost Estimation Model

- Analysis for the Military Aircraft
- WBS Definition
- Cost Drivers Identification
- Data Collection & Analysis
- CER Development
- Cost Factor Identification
- Cost Integration & Verification

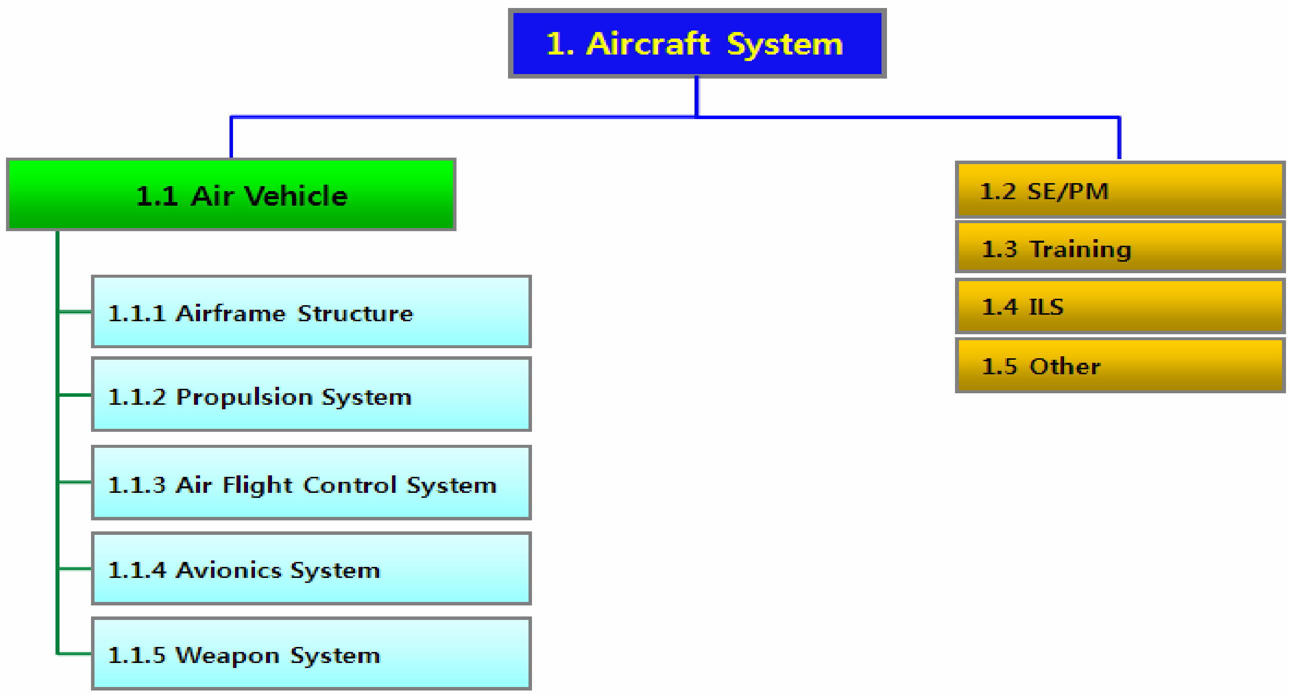
# 1. Analysis ~ 2. WBS Definition



**1. Analysis for the Aircraft System : “Omission”**

**2.** WBS Definition

## A. WBS for Production



# 3. Cost Drivers ~ 4. Data Collection



3. Cost Drivers Identification : **"Omission" (same as R&D)**

**4. Data Collection & Analysis**

A. Cost Drivers Data Collection & Analysis : **"Omission" (same as R&D)**

B. Production Cost Data Collection & Analysis : "Calibration Logic is same as R&D"

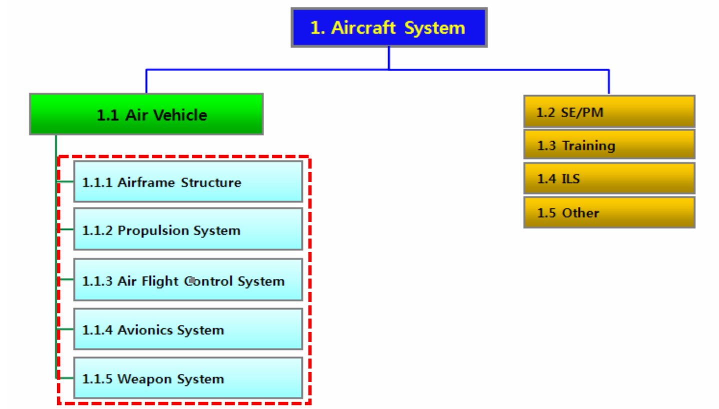
Production Data Format 2

| ※ Production Cost by WBS | KT-1 | KA-1 | T-50 | A-10 | F-15C/D | F-16C/D | F-18E/F | F-22 | F-35A |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 0.08 | | | | |
| | 2012.4 | 2012.4 | 2012.4 | | | | | | |
| 1. Aircraft | ₩10,295,443,985 | ₩13,916,550,011 | ₩50,406,023,664 | ₩23,755,121,216.20 | ₩59,002,903,568.27 | ₩36,975,152,902.78 | ₩79,405,966,064.05 | ₩195,136,139,284.40 | ₩116,714,841,026.59 |
| 1.1 Air Vehicle | ₩9,061,608,117 | ₩12,404,408,071 | ₩44,443,040,751 | ₩16,357,338,226.17 | ₩40,565,366,673.01 | ₩25,162,795,212.98 | ₩61,005,450,067.88 | ₩136,931,103,613.99 | ₩80,193,091,077.12 |
| 1.1.1 Airframe | ₩4,224,650,891 | ₩5,517,507,094 | ₩19,768,359,055 | ₩4,101,445,418.67 | ₩22,048,350,388.17 | ₩7,269,957,573.94 | ₩26,662,151,454.33 | ₩55,237,128,345.26 | ₩32,303,679,532.64 |
| 1.1.2 Propulsion | ₩1,584,973,922 | ₩2,070,018,348 | ₩7,416,549,769 | ₩4,780,673,361.40 | ₩5,670,051,373.51 | ₩4,521,149,328.84 | ₩19,750,522,246.73 | ₩20,858,767,783.22 | ₩12,227,512,633.53 |
| 1.1.3 Air Flight Control System | ₩2,325,971,291 | ₩3,037,780,737 | ₩10,883,890,011 | ₩4,913,137,650.61 | ₩8,604,068,137.10 | ₩8,788,630,991.06 | ₩2,477,082,931.68 | ₩40,505,597,922.80 | ₩23,744,581,438.22 |
| 1.1.4 Avionics | ₩926,012,013 | ₩1,209,396,465 | ₩4,333,077,085 | ₩2,135,417,042.27 | ₩2,197,260,551.09 | ₩3,819,838,508.74 | ₩8,287,869,675.60 | ₩13,219,410,207.58 | ₩7,749,283,514.77 |
| 1.1.5 Weapon System | | ₩569,705,427 | ₩2,041,164,831 | ₩426,664,753.23 | ₩2,045,636,223.15 | ₩763,218,810.39 | ₩3,827,823,759.54 | ₩7,110,199,355.13 | ₩4,168,033,957.97 |
| 1.2 SE/PM | ₩254,619,736 | ₩175,206,896 | ₩0 | ₩1,281,217,329.91 | ₩3,245,228,233.54 | ₩2,291,844,261.80 | ₩1,611,436,275.47 | ₩12,312,021,183.39 | ₩6,415,437,857.70 |
| 1.3 Training | ₩0 | ₩0 | ₩0 | ₩352,771,111.12 | ₩876,211,898.13 | ₩549,092,789.50 | ₩1,252,337,726.87 | ₩2,984,862,495.95 | ₩1,732,170,578.70 |
| 1.4 ILS | ₩730,712,804 | ₩1,336,935,044 | ₩5,962,982,912 | ₩5,763,794,548.99 | ₩14,316,096,763.58 | ₩8,971,420,638.51 | ₩15,536,741,993.83 | ₩42,908,151,991.07 | ₩28,374,141,513.07 |
| 1.5 Other | ₩248,503,328 | ₩0 | ₩0 | ₩0.00 | ₩0.00 | ₩0.00 | ₩0.00 | ₩0.00 | ₩0.00 |

# 5. CER Development



## A. Production CER Development




1. The scope of CER development

   : same as R&D

2. Data used for production CER development(9)

   - KT-1, KA-1, T-50 (ROK) / A-10, F-15E, F-16C/D, F-18E, F-22, F-35A(USA)

3. CER Development Logic

   - No. Production Method : The number of production is included in CER as a cost driver
   - Learning Rate Method :
     * calculate T1 cost by using the number of production and learning rate
     * develop CER for estimating T1 cost with T1 cost and cost drivers data

# 5. CER Development (Cont')



## B. Developed Production CER

### 1. Airframe Structure

- No. Production Method

$$\text{Airframe Prod. cost} = 309 + 0.0179\times(\text{Empty Weight}) - 0.0392\times(\text{No. Production}) - 39.5\times(\text{Span}) + 81.6\times(\text{Turboprop}^{*})$$

*** Correlation of empty Weight and span(0.501)** **(Empty Weight = 2463*(Span) - 7858)**

*** $R^2_{adj}$ = 0.991, MMRE = 0.0629, RMSE = 16.2, PRED(0.25) = 1**

- Learning Rate Method

$$\text{Airframe Prod. cost} = \{-784 + 0.00652\times(\text{Empty Weight}) + 52.0\times(\text{Service Ceiling}) + 28.3\times(\text{G-Limit}) + 49.9\times(\text{Turboprop}^{*})\}\times(\text{No. Production})^{b}$$

*** $R^2_{adj}$ = 0.984, MMRE = 0.0261, RMSE = 32.0, PRED(0.25) = 1**

# 5. CER Development (Cont')



## B. Developed Production CER (Cont')

### 2. Airframe Structure

- No. Production Method

$$\text{Propulsion cost} = \{664 + 0.00731\times(\text{Thrust}) - 43.0\times(\text{Service Ceiling}) - 214\times(\text{Turboprop}^{*})\}\times(\text{No. Production})^{b}$$

*** Correlation of empty Weight and service ceiling(0.804)** **(Empty Weight = 3087*(Service Ceiling) - 26987**

*** $R^2_{adj}$ = 0.990, MMRE = 0.0351, RMSE = 7.2, PRED(0.25) = 1**

- Learning Rate Method

$$\text{Propulsion cost} = 55.3 + 0.00681\times(\text{Empty Weight}) - 0.00655\times(\text{No. Production}) + 22.2\times(\text{G-Limit}) - 17.2\times(\text{Service Ceiling}) - 26.2\times(\text{Turboprop}^{*})$$

*** Correlation of thrust and service ceiling(0.906)** **(Thrust = 2463*(service ceiling) - 7858)**

*** $R^2_{adj}$ = 0.949, MMRE = 0.0814, RMSE = 26.4, PRED(0.25) = 0.89**

# 5. CER Development (Cont')



## B. Developed Production CER (Cont')

3. AFCS

• No. Production Method

$$\text{AFCS cost} = 284 + 0.00737\times(\text{Empty Weight}) - 0.079\times(\text{No. Production}) + 0.0097\times(\text{Thrust}) - 55.0\times(\text{G-Limit}) - 368\times(\text{No. Engine}^{*})$$

*** Correlation of thrust and G-limit(0.597) (Thrust = 6950*(G-limit) - 17440)**

*** $R^2_{adj}$ = 0.995, MMRE = 0.0786, RMSE = 8.8, PRED(0.25) = 1**

• Learning Rate Method

$$\text{AFCS cost} = \{383 + 0.0205\times(\text{Thrust}) + 0.0134\times(\text{Max. Fuel}) - 77.8\times(\text{G-Limit}) - 385\times(\text{No. Engine}^{*}) - 257\times(\text{Fighter}^{*})\}\times(\text{No. Production})^{b}$$

*** Correlation of thrust and G-limit(0.597) (Thrust = 6950*(G-limit) - 17440)**

*** $R^2_{adj}$ = 0.998, MMRE = 0.050, RMSE = 10.5, PRED(0.25) = 1**

# 5. CER Development (Cont')



## B. Developed Production CER (Cont')

4. Avionics

• No. Production Method

$$\text{Avionics cost} = -71.8 + 0.00319\times(\text{Empty Weight}) - 0.00438\times(\text{No. Production}) + 10.2\times(\text{G-Limit}) - 0.0320\times(\text{Combat Range}) + 9.36\times(\text{Turboprop}^{*})$$

*** Correlation of empty weight and combat range(0.475)** **(Empty Weight = 11.8*(combat Range) + 13101)**

*** $R^2_{adj}$ = 0.982, MMRE = 0.050, RMSE = 5.5, PRED(0.25) = 1**

• Learning Rate Method

$$\text{Avionics cost} = \{-651 + 151\times(\ln(\text{Thrust})) - 121\times(\ln(\text{Combat Range}))\} \times(\text{No. Production})^{b}$$

*** Correlation of thrust and combat range(0.610)** **(Thrust = 21.84*(combat Range) + 19239)**

*** $R^2_{adj}$ = 0.888, MMRE = 0.154, RMSE = 28.5, PRED(0.25) = 1**

# 5. CER Development (Cont')



## B. Developed Production CER (Cont')

5. Weapon

- No. Production Method

$$\text{Weapon cost} = 30.3 + 0.00247\times(\text{Empty Weight}) - 0.00462\times(\text{No. Production}) - 4.88\times(\text{Span}) + 15.7\times(\text{Turboprop}^{*})$$

*** Correlation of empty weight and span(0.501)** **(Empty Weight = 2463*(Span) - 7858)**

*** $R^2_{adj}$ = 0.942, MMRE = 0.1323, RMSE = 5.54, PRED(0.25) = 0.75**

- Learning Rate Method

$$\text{Weapon cost} = \{-52 + 0.00201\times(\text{Empty Weight}) + 7.24\times(\text{G-Limit})\}\times(\text{No. Production})^{b}$$

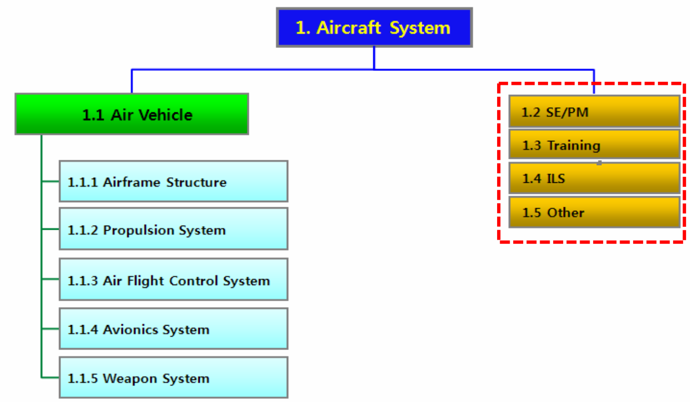
*** $R^2_{adj}$ = 0.969, MMRE = 0.066, RMSE = 5.4, PRED(0.25) = 1**

# 6. Factor Estimation Relationship(FER)



## A. R&D FER Development

1. The scope of FER development




2. Cost Factors Ratio

- ROK : Missile cost Estimation Model in previous study
- USA : USA FAA Cost Factor Ratio
- The differences of ROK and USA are so big.
- So we applied ROK cases mostly.

| | 1.1 Air Vehicle | 1.2 SE/PM | 1.3 Training | 1.4 ILS |
|---|---|---|---|---|
| KT-1 | 100 | 2.81 | - | 8.06 |
| KA-1 | 100 | 1.41 | - | 10.78 |
| ROK Ave. | 100 | 2.11 | - | 9.42 |
| A-10 | 100 | 7.83 | 2.16 | 35.24 |
| F-15E | 100 | 8.00 | 2.16 | 35.29 |
| F-16C/D | 100 | 9.11 | 2.18 | 35.65 |
| F-18E | 100 | 2.64 | 2.05 | 25.47 |
| F-22 | 100 | 8.99 | 2.18 | 31.34 |
| F-35A | 100 | 8.00 | 2.16 | 35.38 |
| Thypoon | 100 | 8.24 | 2.16 | 47.00 |
| USA Ave. | 100 | 7.54 | 2.14 | 35.05 |
| Min | 100 | 1.41 | 2.05 | 8.06 |
| Total Ave. | 100 | 5.84 | 2.14 | 27.23 |
| Max | 100 | 9.11 | 2.18 | 47.00 |

# 7. Integration & Verification



## A. Integration

| WBS | | | | Cost Estimation Logics |
|---|---|---|---|---|
| Aircraft | Air Vehicle | Airframe | No.Prod. | $WC_{1-N}$ = 309 + 0.0179×(Empty Weight) − 0.0392×(No. Production) − 39.5×(Span) + 81.6×(Turboprop*) |
| | | | Learning | $WC_{1-L}$ = {− 784 + 0.00652×(Empty Weight) + 52.0×(Service Ceiling) + 28.3×(G-Limit) + 49.9×(Turboprop*)}×(No. Production)$^{b}$ |
| | | Propulsion | No.Prod. | $WC_{2-N}$ = 55.3 + 0.00681×(Empty Weight) − 0.00655×(No. Production) + 22.2×(G-Limit) − 17.2×(Service Ceiling) − 26.2×(Turboprop*) |
| | | | Learning | $WC_{2-L}$ = {664 + 0.00731×(Thrust) − 43.0×(Service Ceiling) − 214×(Turboprop*)}×(No. Production)$^{b}$ |
| | | AFCS | No.Prod. | $WC_{3-N}$ = 284 + 0.00737×(Empty Weight) − 0.079×(No. Production) + 0.0097×(Thrust) − 55.0×(G-Limit) − 368×(No. Engine*) |
| | | | Learning | $WC_{3-L}$ = {383 + 0.0205×(Thrust) + 0.0134×(Max. Fuel) − 77.8×(G-Limit) − 385×(No. Engine*) − 257×(Fighter*)} ×(No. Production)$^{b}$ |
| | | Avionics | No.Prod. | $WC_{4-N}$ = − 71.8 + 0.00319×(Empty Weight) − 0.00438×(No. Production) + 10.2×(G-Limit) − 0.0320×(Combat Range) + 9.36×(Turboprop*) |
| | | | Learning | $WC_{4-L}$ = {− 651 + 151×(ln(Thrust)) − 121×(ln(Combat Range))} ×(No. Production)$^{b}$ |
| | | Weapon | No.Prod. | $WC_{5-N}$ = 30.3 + 0.00247×(Empty Weight) − 0.00462×(No. Production) − 4.88×(Span) + 15.7×(Turboprop*) |
| | | | Learning | $WC_{5-L}$ = {− 52 + 0.00201×(Empty Weight) + 7.24×(G-Limit)} ×(No. Production)$^{b}$ |
| | SE/PM | | | $WC_6 = 0.0211 \times (\sum_{i=1}^{5} WC_{i-N})$ or $0.0211 \times (\sum_{i=1}^{5} WC_{i-L})$ |
| | Training | | | $WC_7 = 0.0214 \times (\sum_{i=1}^{5} WC_{i-N})$ or $0.0214 \times (\sum_{i=1}^{5} WC_{i-L})$ |
| | ILS | | | $WC_8 = 0.0942 \times (\sum_{i=1}^{5} WC_{i-N})$ or $0.0942 \times (\sum_{i=1}^{5} WC_{i-L})$ |

# 7. Integration & Verification (Cont')

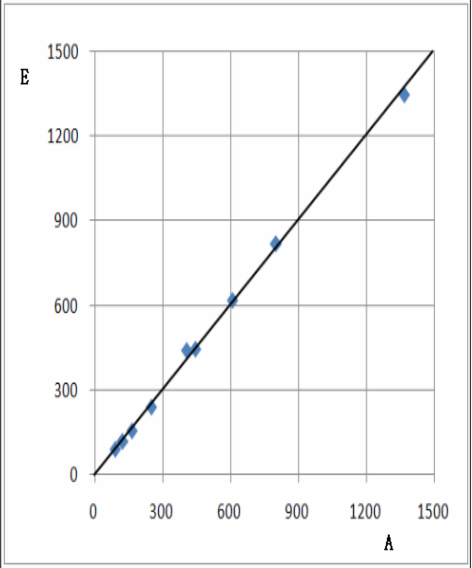


## B. Verification

- MMRE and the Comparison of estimated and actual
- Compared actual and estimated only by CER elements(Air vehicle)

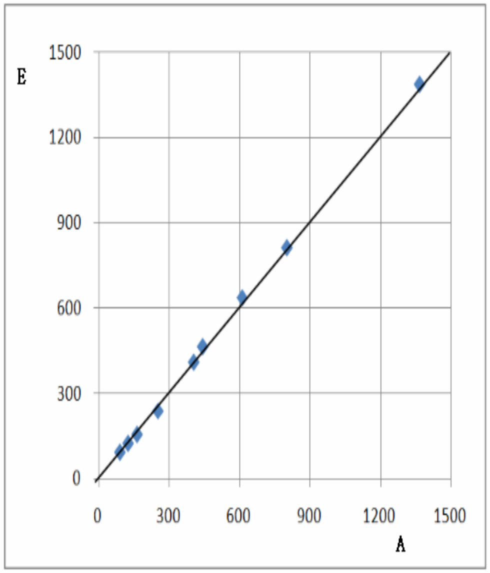
### • No. Production Method

| | Actual (A) | Estimated (E) | MRE |
|---|---|---|---|
| KT-1 | 90.62 | 88.40 | 0.02 |
| KA-1 | 124.05 | 118.50 | 0.04 |
| T-50 | 444.43 | 443.45 | 0.00 |
| A-10 | 163.57 | 154.70 | 0.05 |
| F-15E | 405.65 | 440.40 | 0.09 |
| F-16C/D | 251.63 | 237.07 | 0.06 |
| F-18E | 610.06 | 617.59 | 0.01 |
| F-22 | 1369.31 | 1343.57 | 0.02 |
| F-35A | 801.94 | 817.57 | 0.02 |
| MMRE = 0.0355 | | | |




### • Learning Rate Method

| | Actual (A) | Estimated (E) | MRE |
|---|---|---|---|
| KT-1 | 90.62 | 93.15 | 0.03 |
| KA-1 | 124.05 | 126.17 | 0.02 |
| T-50 | 444.43 | 463.32 | 0.04 |
| A-10 | 163.57 | 154.72 | 0.05 |
| F-15E | 405.65 | 409.29 | 0.01 |
| F-16C/D | 251.63 | 240.11 | 0.05 |
| F-18E | 610.06 | 636.26 | 0.04 |
| F-22 | 1369.31 | 1387.07 | 0.01 |
| F-35A | 801.94 | 814.07 | 0.02 |
| MMRE = 0.0297 | | | |




The developed models can be applicable in earlier phases of acquisition because their relative errors are lower than 5%

# Risk Analysis Method

- Risk Analysis Method
- Risk Analysis Example

# Risk Analysis Method



## A. Identify distribution of each WBS cost estimation logics

- CER Elements : Normal Distribution
  - * Parameters → Average : Estimated value, Standard Error : RMSR of CER
- FER Elements : Triangle Distribution
  - * Parameters → Min., Average, Max. values of collected data

## B. Applied Risk Cost Generation Method

- We used Monte Carlo and Latin Hypercube simulation method
- Simulation Tool : R package

# Risk Analysis Example



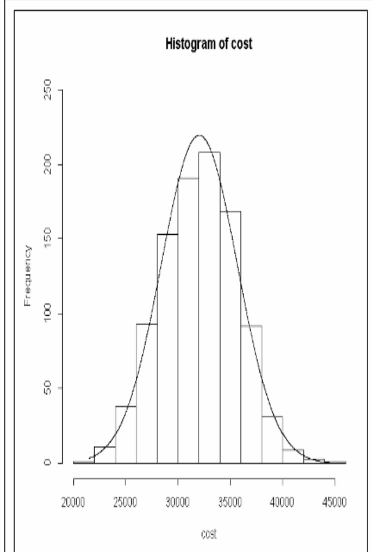
## B. T-50 case

- T-50 R&D Cost Case

| WBS | | | Logic | Distribution | Ave. | | Stad. Error |
|---|---|---|---|---|---|---|---|
| | | | | | Min | Ave. | Max |
| Aircraft | Air Vehicle | Airframe | CER | Normal | 7521 | | 2961 |
| | | Propulsion | CER | Normal | 2980 | | 840 |
| | | AFCS | CER | Normal | 3085 | | 579 |
| | | Avionics | CER | Normal | 1852 | | 341 |
| | | Weapon | CER | Normal | 1085 | | 397 |
| | I&T | | FER | Triangle | 7% | 12% | 25% |
| | SE/PM | | FER | Triangle | 2% | 6% | 13% |
| | T&E | | FER | Triangle | 16% | 23% | 57% |
| | Tool & Equip. | | FER | Triangle | 6% | 12% | 33% |
| | Data | | FER | Triangle | 1% | 2% | 5% |
| | Training | | FER | Triangle | 1% | 10% | 17% |
| | ILS | | FER | Triangle | 3% | 9% | 23% |

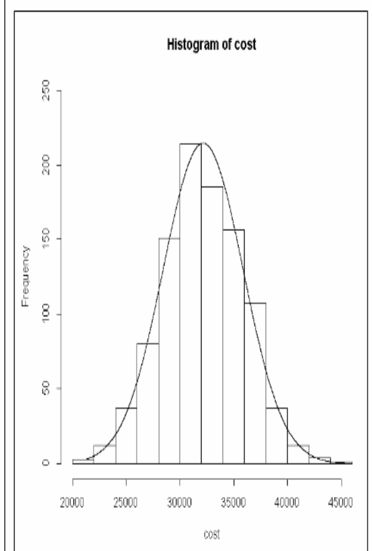
**Monte Carlo / Latin Hypercube Simulation**

Monte Carlo Simulation




| Min. | Max. | Ave. | Stad. Error |
|---|---|---|---|
| 21474 | 44500 | 32019 | 3639 |

Latin Hypercube Simulation




| Min. | Max. | Ave. | Stad. Error |
|---|---|---|---|
| 21275 | 45355 | 32148 | 3719 |

# Conclusion

# Conclusion



**This study has proposed a CER development methodology which has enabled the overcoming of the restrictions of an insufficient amount of weapon system R&D, production data under the DoD acquisition environment in Korea.**

# Thank you

# (Q&A)