Aircraft Design Optimization Process using a Decision Model by Database*

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In this study, an efficient methodology capable of systematically constructing an aircraft design database is developed and its application is discussed. The database focuses on fighter and attack aircraft because their design is a particular challenge compared with the design of other types of aircraft. For small conventional aircraft, historical information accumulated over many years on countless previous designs is freely available to designers. Such data for fighter aircraft design are, however, difficult to obtain or are insufficient. The database developed can contribute to the design of fighter and attack aircraft on a conceptual level. In addition, decision-making models are developed by means of data mining as well as approximation models based on the developed database to facilitate initial aircraft configuration decisions. The efficiency and simplicity of the proposed method are described in a case study, which also describes a sample process of conceptual design optimization using initial design information extracted from the developed database.

Key Words: Response Surface Methodology, Data Mining, Decision Model, Database, Optimization

1. Introduction

The designing of aircraft is an inherently complex process. Numerous methodologies, tools and software packages are available for aircraft design. Advanced design methodologies have led to significant increases in computation cost and time as the level of complexity of the analysis tool increases. These depend on many factors such as customer and manufacturer demand, safety protocols, accuracy level, etc. The design process starts with the aircraft's intended purpose. Aircraft performance requirements differ according to the purpose for which they are intended. In the case of aircraft design, engineers try to envision all the possible decisions that must be made during each design phase and how they are affected by the various performance targets and applications the aircraft will be required to fulfill. These design decisions should be made by an expert designer who knows the advantages and disadvantages of each. The complex interaction between design decisions, their justification and their influence on other aspects of design must be modeled accurately, covering as broad a base as possible to handle diverse mission goals. For this reason, aircraft design is quite a complex and lengthy process. There is a need to build a model to assist decision-making by designers to reduce complexity and save time. Two such techniques are data mining, which derives useful information and relationships between data from a database, and the response surface methodology (RSM) approximation technique, both of which are applied in the construction of decision models in this study.^{1–4)} As a consequence, there is a need for a large amount of information. Databases are set up to allow users to access data efficiently. They are created for various purposes and applied in different ways. Development of ad-

equate databases and their efficient application are increasingly required.

This study describes the efficient application of a database using a decision-making model for aircraft design which also describes a process of conceptual design optimization using an initial design derived from decision-making models. This design process is especially focused on fighter and attack aircraft because of the difficulty of obtaining adequate data at reasonable cost, whereas general specifications for commercial aircraft are widely available.

2. Process and Methodology

The approach introduced in this study begins with the systematic construction of an aircraft database. It is developed in stages by using insufficient information from open sources and public sources. Additionally, approximation models and sensitivity analysis are implemented and applied to predict missing data in the database.^{5–7)} Analysis methods are developed for aerodynamics, propulsion and performance.^{8–10)} These analysis codes are implemented in a spreadsheet using the well-known Visual Basic for applications (VBA) programming language for simple and efficient calculation.^{11–13)} The developed database contains complete information for 43 different types of fighter and attack aircraft. The process can predict complete information for new aircraft from partial information.

The next step in the methodology is the efficient application of the developed database. Decision-making models are constructed based on the database using data mining and approximation techniques.¹⁴⁾ The implemented decision models provide an initial design configuration of new aircraft concepts based on a set of performance requirements. After that, a design optimization process is set up using these initial design configurations. An overview of the process is described in Fig. 1.

Fig. 1. Aircraft design process in database development.

3. Systematic Database Development Process

In the database development process, the implementation steps are classified according to the data available for fighter and attack aircraft. A parameter-based database development process is used. The main three steps are set up as follows:

- database construction using public domain sources
- database construction using approximation technique
- database construction using analysis tools

The detailed process of database development can be seen in Fig. 2. In this figure, the left-hand side describes the database development and the right-hand side the application process of the implemented database.

3.1. Database construction from public domain sources

The basic configuration database for 43 aircraft was constructed according to the first step of the database construction process. The configuration data for fighter and attack aircraft was collected as much as possible from public domain sources and publications. The utilized publications included *Jane's All the World's Aircraft*,¹⁵⁾ *The World's Great Attack Aircraft*,¹⁶⁾ *The Illustrated Directory of Fighters*,¹⁷⁾ and *An Illustrated Guide to Modern Fighters and Attack Aircraft*.¹⁸⁾ Various types of aircraft were included in the database.

3.2. Database construction using approximation technique

A preliminary database was developed from public do-

main sources and publications. In many cases, insufficient data was available to fully populate every attribute of a given aircraft. The missing data was estimated using RSM-based approximation.

RSM is an empirical modeling approach using polynomials as local approximations of the true input/output relationship.^{7,19)} Generally the second-order polynomial function is used for the design variables to represent the response surface.²⁰⁾

$$y_{\text{predict}} = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=2}^k b_{ij} x_i x_j \quad (1)$$

where $x_1, x_2, \dots, x_k$ are the design variables which affect the response, b_i ($i=1, 2, \dots, k$) are the coefficients of the regression function, and y_{predict} is the predicted value from the regression function.

Sensitivity analysis was performed to identify sensible design variables and parameters before implementation of the approximation functions.^{5,21)} Based on an empirical and theoretical equation relationship, a set of design variables for the specific response parameter was selected for sensitivity analysis. Then, RSM was iteratively performed using the most influential design variables from the sensitivity analysis. The accuracy of the approximation model was checked with adjusted R^2 . The typical range was between 0.9 and 1.0.¹⁹⁾ The approximation function with adjusted R^2 values

Fig. 2. Database development process.

was obtained. The detailed flow process is described in Fig. 3.

$$R_{adj}^2 = 1 - \frac{SSE/(n-p)}{SST/(n-1)} \quad (2)$$

where SSE and SST are the error sum of squares and total sum of squares, respectively. The variable, n , is the number of experimental points and p is the number of response function coefficients.

Missing data in fuel weight, leading-edge sweep angle, and SFC with afterburner and without afterburner were predicted with the approximation function. The process of developing fuel weight approximation using RSM is described below. Table 1 describes the number of design variables for the approximation function and their adjusted R^2 values for fuel weight. The priorities of described design variables were obtained from sensitivity analysis.

After comparison of these three cases, the set of design variables with the highest adjusted R^2 value was chosen to create the approximation function. Thus, the empty weight and aspect ratio became design variables for constructing the fuel weight approximation function.

$$\text{fuel weight} = f(\text{empty weight, aspect ratio}) \quad (3)$$

Validations of the approximate values for fuel weight for the selected aircraft are shown in Table 2. Similarly, approximation functions for leading-edge sweep angle, and specific

Fig. 3. Approximation library construction flowchart.

Table 1. Comparison of adjusted R^2 for fuel weight.

Response	Number of design variables	List of design variables	Adjusted R^2
Fuel weight	2 variables	Empty weight Aspect ratio	0.92
	3 variables	Empty weight Aspect ratio Max. speed	0.91
	4 variables	Empty weight Aspect ratio Max. speed MTGW	0.90

Table 2. Validation of approximate values for fuel weight.

Name	AR	W_{empty} (lb)	W_{fuel} (lb) (real data)	W_{fuel} (lb) (approximated data)	Err. %
AIDC F-Ck-1	3.66	14299.14	12300.81	10382.13	15.59%
Su-30	3.49	39021.81	36637.62	31686.09	13.51%
F1	2.82	16314.22	14126.67	13373.93	5.32%

Table 3. Validation of approximation function.

Approximation function	Real data	Approximated data	Err. %
Leading-edge sweep angle	33.01	31.10	5.78%
SFC with afterburner	1.92	1.86	3.12%
SFC without afterburner	0.81	0.82	2.50%

fuel consumption (SFC) with afterburner and without afterburner were also applied to predict missing data in the developed database. Validation of these functions can be seen in Table 3.

3.3. Database construction using analysis tools

Analysis based on systematic empirical and theoretical equations for the performance, aerodynamics and propulsion of aircraft was conducted. By this means, aircraft data can be calculated quickly and with reasonable accuracy from a minimal set of known parameters. All analysis codes were implemented with VBA. This allows the functions to be used smoothly and in a user-friendly manner by setting the input values in the functions like a spreadsheet's built-in function.^{11,13)}

The aircraft's component weights were calculated using configuration data. Total aircraft empty weight was obtained by summing up the component weights. Statistically-derived weight estimation equations for fighter and attack aircraft were implemented. The weight components were wing weight, vertical tail weight, fuel system and tank weight, engine weight, engine selection weight, engine mount weight, etc. Total aircraft weight was calculated by summing the aircraft empty weight, fuel weight and payload weight.

Lift coefficient and drag coefficient were calculated in an aerodynamic analysis module. Parasite drag and induced drag were also calculated. The component build-up method was used in C_{d0} calculation. Maximum climb angle, climb rate, limited bank angle, maximum turning rate, stall speed and range calculations were considered and implemented in the performance analysis. Specific fuel consumption and

Fig. 4. Comparison of C_{d0} for generic fighter aircraft.

Table 4. Validation of analysis results.

Name	Parameter	Calculated data	Test data	Err. %
Generic fighter aircraft	Stall speed (knot)	107.89 (50% of fuel, plain flap)	110.01 (50% of fuel)	1.93%
	F-16 C Max. climb angle (deg)	34.37	33.91	1.36%
Generic fighter aircraft	Max. rate of climb (ft/s)	544.81	570.76	4.57%
F-22	Turning rate (deg/s) (sustained turn rate)	19.49	20.07	2.89%
Generic fighter aircraft	Fuel flow (with maximum thrust) (without afterburner)	9656.25	9659.28	0.03%

fuel flow were also calculated from empirical equations. The analysis codes produced results in very close agreement with published data. Validations are also described in this section. The validation of C_{d0} for generic fighter aircraft is illustrated in Fig. 4.

The validation of the analysis code for the performance, propulsion and aerodynamics parameters of the selected aircraft is shown in Table 4.

A database for 43 different types of fighter and attack aircraft with complete information such as general configuration, weight information, performance, aerodynamics and propulsion data was constructed using the database development process described in this study. The next section describes the efficient application of the database as a decision model to aid initial design consideration.

4. Decision-making Modeling Process

In the decision-making modeling process, decision models were used to derive an initial aircraft configuration from the fighter and attack aircraft database to assist decisions of designers. This process transforms large amounts of data into meaningful patterns and rules. The detailed process is described in Fig. 5. A predicted initial aircraft configuration was used in the optimization process. The decision models were generated by data mining and an approximation technique according to data type.²²⁾ Data mining is a computational technique that computes decision models useful for

Fig. 5. Decision-making modeling process.

classifying and predicting the behavior of new data.^{23,24)} Data mining techniques can perform well with discrete types of data. On the other hand, approximation techniques with sensitivity analysis can handle numeric data types more accurately.

4.1. Database for decision-making model

In order to create a good decision model, an existing data set with a known output was constructed and decision models were built from the database. Aircraft configurations were predicted from the performance of the aircraft. To find data relationships between performance parameters and configurations, the database which included both parts was reclassified. A limited number of performance parameters were accessed in this research because of the small capacity of the database. A list of data included in the reclassified database for the decision-making model is provided in Table 5.

4.2. Implementation of decision-making model

The reclassified database allowed empirical decision models to be generated using two techniques according to data type. The constructed decision models are listed in Table 6.

4.2.1. Implementation by data mining techniques

Data mining analysis includes algorithms such as regres-

sion, classification, clustering and nearest neighbor. A classification algorithm, also known as classification tree or decision tree, was utilized in this study to realize the decision-making model. This algorithm can create a step-by-step guide for how to determine and predict the output for new data instances. Weka data mining software was used for construction of the decision models. Among several data mining algorithms, the J48 decision tree algorithm was chosen to implement a decision tree model. These decision models also perform selection of the most related attributes in the process.

Generating a decision tree model for vertical tail number selection based on the prepared database is shown in Fig. 6. As shown in the figure, the first splitting attribute was stall speed. If the stall speed is less than 134.54, that branch will give one result. If the stall speed is greater than 134.54, two new branches split at that node. By following these branches the final decision is obtained from the decision tree. Using this decision model, vertical tail numbers can be predicted by setting the decision factors as input for new aircraft. Other predicted general arrangements provided by the data mining technique for discrete data are described in Table 11.

Table 5. Database for decision-making model.

	Description	Unit	A1	A2	A3
Performance data	Name	—	F-4E Phantom II	MiG-29	—
	Crew	—	2	1	—
	Stall speed	knot	143.17	125.29	—
	Max. Mach number	—	2.23	2.25	—
	Range	km	2600	1430	—
	Load factor	—	10.50	9.00	—
	Turning rate	deg/s	12.56	15.24	—
	Bank angle	deg	76.74	75.52	—
	Payload weight	lb	14806.09	12570.12	—
Configuration data	Aircraft type	—	Fighter	Fighter	—
	Engine number	—	2	2	—
	Vertical tail number	—	1	2	—
	Canard (with or without)	—	no	no	—
	Engine number	—	2	2	—
	Wing area	ft ²	530	409	—
	Sweep angle	deg	45	42	—
	Aspect ratio	—	2.77	3.39	—
	Taper ratio	—	0.18	0.31	—
	Fuselage length	ft	59.27	46.56	—
	Fuselage width	ft	4.15	3.19	—
	Fuselage height	ft	5.92	5.17	—
	HT aspect ratio	—	2.58	2.42	—
	HT taper ratio	—	0.34	0.73	—
	HT volume coefficient	—	0.13	0.19	—
	VT aspect ratio	—	0.48	0.34	—
	VT taper ratio	—	0.35	0.24	—
	VT volume coefficient	—	0.02	0.06	—

Table 6. List of decision models.

Implementation by data mining techniques for discrete data	
General aircraft configuration	Aircraft types, engines number, vertical tail number
Implementation by approximation techniques for numeric data	
Wing	Wing area, sweep angle, aspect ratio, taper ratio
Fuselage	Fuselage length, fuselage width, fuselage height
Horizontal tail	HT aspect ratio, HT taper ratio, HT volume coefficient
Vertical tail	VT aspect ratio, VT taper ratio, VT volume coefficient

Fig. 6. Decision tree for vertical tail number selection.

(a) Sweep angle sensitivity analysis

(b) Wing area sensitivity analysis

Fig. 7. Sensitivity analysis.

4.2.2. Implementation by approximation techniques

Decision models for wing, fuselage, horizontal tail, and vertical tail with numeric data were implemented by means of approximation techniques. The detailed process was described in section 3.2. Sensitivity analysis was performed before constructing the approximation function. The five most related design variables were chosen for the approximation function for each aircraft configuration using sensitivity analysis. Sensitivity analyses for sweep angle and wing area are described in Fig. 7. According to Fig. 7(a), maximum Mach number is mainly related to sweep angle and stall speed is secondly related to sweep angle. In Fig. 7(b), maximum Mach number and range are firstly and secondly related with wing area, respectively. The predicted results for initial air-

craft configuration by the approximation technique for numeric data are also described in Table 11.

5. Case Study

In order to demonstrate the benefits of the database development process and its application in developing an efficient decision-making model for aircraft initial design, a case study was carried out.

5.1. Database prediction for new aircraft using the database development process

To test the feasibility, effectiveness and speed of the database development process, a new aircraft not included in the database with insufficient data was selected. The selected air-

Table 7. Database construction using public domain sources for the Mitsubishi ATD-X.

Database construction using public domain sources	
Type	Fighter
Name	Mitsubishi ATD-X
Country	Japan
Max G	-3/+9
Empty weight (lb)	26455.47
Thrust (lb)	22046
Wing area (ft ²)	377.55
Wing span (ft)	29.85
Cruise altitude (ft)	35000
Thrust (lb) (with afterburner)	33069
Max. speed (knot) (sea level)	687.78

Table 8. Database construction using approximation techniques for the Mitsubishi ATD-X.

Database construction using approximation techniques	
Fuel weight (lb)	18912.42
Leading-edge sweep angle (deg)	54.20
SFC (lb/lbf-hr) (without afterburner)	0.78
SFC (lb/lbf-hr) (with afterburner)	2.05
Cruise speed (knot)	1043.14

Table 9. Database construction using analysis tools for the Mitsubishi ATD-X.

Database construction using analysis tools	
Min. speed (knot)	203.05
C_{d0} (at $M=0.8$, 10000 ft)	0.01
Maximum climb angle (deg)	41.94
Maximum turning rate (ft/s)	16.13
Limit by bank angle (deg)	75.52
Fuel flow (lbm/hr) (without afterburner) (at maximum thrust)	17195.88
Fuel flow (lbm/hr) (with afterburner) (at maximum thrust)	67791.45

craft was the Mitsubishi ATD-X.¹⁵⁾ This is a prototype fifth-generation jet fighter. Table 7 shows the database construction from public domain sources for the Mitsubishi ATD-X aircraft.

Using the approximation function implemented from the constructed database, the parameters described in Table 8 can be predicted.

The aerodynamics, performance and propulsion parameters for the Mitsubishi ATD-X aircraft were computed using the analysis tools. The data is described in Table 9.

Finally, a design database for a new fighter aircraft, Mitsubishi ATD-X, was developed successfully and efficiently using the implemented database development process.

5.2. Design optimization process for fighter aircraft

A case study for a design process was performed for the F-CK-1 Ching-kuo aircraft.¹⁵⁾ It is a fourth-generation jet fighter aircraft.

5.2.1. Prediction of initial aircraft configuration

In the case study of the decision-making model, performance requirements were set to be equal to the performance of existing F-CK-1 aircraft in the implemented database in order to assess the quality of results. The set of performance

Table 10. Input for decision models.

Description	Unit	F-CK-1 aircraft
Crew	—	2
Stall speed	knot	130
Max. Mach number	—	1.8
Range	km	1100
Load factor	—	9.1
Turning rate	deg/s	12
Bank angle	deg	75.6
Payload weight	lb	400

Table 11. Output of decision models.

Data type	Group	Description	Unit	Decision models output	F-CK-1 aircraft	Err. %
Discrete data	General aircraft configuration	Aircraft type	—	Fighter	Fighter	—
		Engine number	—	2	2	—
		Vertical tail number	—	1	1	—
Numeric data	Wing	Wing area	ft ²	270.59	260.00	3.91
		Sweep angle	deg	41.31	37.00	10.43
		Aspect ratio	—	3.78	3.69	2.38
		Taper ratio	—	0.28	0.26	7.14
	Fuselage	Fuselage length	ft	38.20	33.75	11.65
		Fuselage width	ft	9.21	10.08	-9.45
		Fuselage height	ft	5.54	4.98	10.11
	Horizontal tail	HT aspect ratio	—	3.44	3.78	-9.88
		HT taper ratio	—	0.34	0.30	11.76
		HT volume coefficient	—	0.33	0.37	-12.12
	Vertical tail	VT aspect ratio	—	0.48	0.49	-2.08
		VT taper ratio	—	0.28	0.27	3.57
		VT volume coefficient	—	0.06	0.05	13.33

data is described in Table 10. The results of decision-making models are shown in Table 11. These results matched well the configuration of the F-CK-1 aircraft.

5.2.2. Design formulation

In this study, the objective function was to minimize the maximum take-off gross weight subject to performance requirements, and this was a function of the design variables. Decision-making models and analysis tools were implemented by means of spreadsheets and VBA for simple and efficient handling and updating of the information. Thus, the optimization process was performed in a spreadsheet. An optimizer was applied with the generalized reduced gradient method.²⁵⁾ In order to reduce the computational time, four design variables were chosen, as presented in Table 12. Constraints are described in Table 13. In order to assess the quality of the results, the performance constraints were set to be equal to the performance of the AIDC F-CK-1 Ching-kuo aircraft.

The aircraft included in the developed database were for the period 1950 to 2010. Average values were analyzed by decade for each aircraft parameter. The approximated historical trends and R^2 values are described in Fig. 8. Fudge factor, 0.976, 0.951 and 0.980 for empty weight, range and stall speed, were derived from the approximated historical trends to correct aircraft parameters during the analysis.

5.2.3. Optimization results and discussion

The optimizer was set to minimize the maximum take-off gross weight while meeting performance constraints equal to the performance of the AIDC F-CK-1 Ching-kuo aircraft.

Fig. 8. Approximated historical trends.

The optimization process was carried out for two cases. The first optimization process was performed using initial aircraft configurations that were predicted by the decision models with the same target performance attributes as the F-CK-1 aircraft. The predicted initial aircraft configurations are shown in Table 11. The second optimization process was carried out setting the initial aircraft configuration randomly. The design generated by the optimizer for the two cases can be seen in Table 14. A comparison of the convergence history for the two cases is described in Fig. 9. The optimization process with smart prediction of the initial design by decision model generated the results in less iteration than the optimization process with random selection of the initial design.

This design process and its systematical database development process can also be applied for different aircraft types, such as commercial transport aircraft and general aviation aircraft. In construction of the decision models, a limited set of performance data is used to predict configuration. More performance data is needed for better prediction by physical and data relationships. Additional configurations such as location and detail information of wing, horizontal tail and vertical tail need to be inserted into the database.

Table 12. Design variables.

	Description	Unit	x_{lb}	x_{ub}
1	Wing area	ft ²	226	375
2	Sweep angle	deg	35.00	55.50
3	Wing aspect ratio	—	1.75	5.33
4	Wing taper ratio	—	0.10	0.56

Table 13. Design constraints.

	Description	Unit	Goal	Condition
C1	Empty weight	lb	≤ 14299	Weight
C2	Range	km	≥ 1100	Performance (max. range)
C3	Climb rate	ft/s	≥ 300	Performance (at climb condition)
C4	Turning rate	deg/s	≥ 12	Performance (sustained turn rate)
C5	Stall speed	knot	≤ 130	Performance (plain flap)
C6	Turning radius	ft	≤ 1526	Performance (at max. load factor)

Table 14. Optimization results.

	Description	Unit	Initial design using decision model	Optimization results (Case 1)	Initial design using random selection	Optimization results (Case 2)
	Iteration number			12		16
Objective function	MTGW	lb	26676.49	25090.12	26976.31	24937.69
Design variables	Wing area	ft ²	270.59	261.94	291.00	265.43
	Sweep angle	deg	41.31	53.00	35.00	49.20
	Wing aspect ratio	—	3.78	3.26	3.50	3.21
	Wing taper ratio	—	0.28	0.21	0.30	0.25
Constraint	Empty weight	lb	14299	12389.29	14585.27	12559.86
	Range	km	1100	1119.83	1093.64	1122.39
	Climb rate	ft/s	300	325.43	304.19	335.75
	Turning rate	ft/s	12	14.57	13.29	14.24
	Stall speed	knot	130	129.02	126.91	127.76
	Turning radius	ft	1526	1523.46	1858.27	1521.04

Fig. 9. Convergence history.

6. Conclusion

An efficient process for fighter and attack aircraft database development and prediction of initial design configuration using decision models for optimization has been successfully developed. The implemented process began with the development of a fighter and attack aircraft database that was constructed using a systematic process. Configuration, performance, aerodynamics and propulsion data of 43 fighter and attack aircraft were included in the database. This database development methodology can be used to predict data for new fighter and attack aircraft where insufficient data is known. The approximation function and analysis tools have been validated, and the results indicate the accuracy, simplicity and quickness of the developed methodology. The developed database was then implemented to predict the initial configuration of new design concepts using decision models. The process was validated using performance data of existing fighter aircraft as the input for the implemented decision models. Predicted initial configuration data was applied to a design optimization process. Through this process, a new aircraft design with better performance than the reference aircraft was obtained, and it can reduce iteration steps when compared to the process with random selection of the initial design.

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