A Web-based Computer-Aided Material-Selection System for Aircraft Design

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***Abstract*—A web-based computer-aided material-selection system for aircraft design was put forward, applying a material-selection strategy combined screening and ranking methods. This combined strategy could make good use of selection experience and material testing data, thus making the selection results more reasonable and bringing more standardization to the material selection process. The system's Browser/ Server (B/S) architecture together with its implementation details was described. The B/S system could be accessed with web browser conveniently. The system's effectiveness was demonstrated by two aircraft-design material-selection case in actual applications. This system could help designer select suitable materials for airframe, provide knowledge for inexperienced engineer and accumulate enterprise-level material-selection expertise.**

***Index Terms*—aircraft design, materials selection, expert system, web-based system**

I. Introduction

Material selection, a critical element in mechanical design process, is usually an empirical task. In recent years, many new materials are adopted to reduce weight and improve performance; moreover, there are more material factors need to be taken into consideration [1]. Unfortunately, some of the factors are contradictory. It is hard for a design engineer, especially an inexperienced one, to select proper materials for structural components. This issue brings with it the field of quantitative material selection method [2] and computer-aided material-selection system in mechanical design [3].

Though there are a variety of quantitative material-selection methods available, such as Simple Additive Weighting (SAW) [4-7], ELECTRE [8-11], TOPSIS [10,12-16], VIKOR [11,17] and GA method [18], none of these methods have evolved from a pedagogical method into systems closer to the needs of design engineers. These quantitative methods are mostly based on Multiple Criteria Decision Making (MCDM) theory.

In recent years, a few computer-aided material-selection systems are developed, mostly based on expert system theory. Trethewey et al. [19] develops a knowledge-based system for materials management and selection. Amen et al. [20] builds up a case-based reasoning system to select material/heat treatment process. Sapuan et al. [21] takes rule-based reasoning for automotive components and establishes a knowledge-based system for material selection of polymeric-based composites. Sapuan et al. [22] proposes a prototype knowledge based system for material selection of ceramic matrix composites for engine components like piston, connecting rod and piston ring. These traditional systems have following limitations [23-25]:

(1) Lower availability to provide the expertise at the place and time where it is needed;

(2) Inconvenience in updating the software and interface;

(3) A lack of common protocols for exchange of knowledge in a concurrent or collaborative framework.

Internet technology has changed the prospects of expert system and led to the emergence of web-based expert system. Grove [23] and Duan et al. [24] both give some examples of web-based expert systems, e.g. WITS. For material selection in mechanical design, Zha [26] constructs a web-based advisory system for qualitative selection of material/process in the phase of conceptual design.

To develop the pedagogical material-selection methods or systems into a practical system tailored to the needs of design engineers, a number of studies were carried out:

The US National Materials Advisory Board convened a committee to study the application of expert systems to materials selection during structural design [27]. Ashby [3] proposed strategies for selecting materials and processes. Edwards [28] developed a computerised questionnaire to support material selection in conceptual design. Deng et al. [29] analysed the role of material identification and selection in engineering design. Van Kesteren [30] identified the information needs of product designers and presented these needs in a comprehensive way for material information developers. Jahan et al. [1] presented a review study of material selection methods over the past two decades. Ramalhete et al. [31] carried

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out a bibliographical search on selection methods, databases and software for material selection and tried to answer questions about how these digital tools work, what properties determine the selection and what kind of information results from the selection. To help designers search for suitable MCDM methods for different material selection problems, Cicek et al. [32,33] proposed a modified fuzzy axiomatic design-model selection interface (FAD-MSI) and an integrated decision aid (IDEA), respectively.

In this paper, a web-based computer-aided material-selection system for aircraft design is proposed to meet the demand of concurrent engineering. Also the system is expected to be compatible with the aircraft development environment in an enterprise. Specially, a case database is designed to save user's historical material-selection data as well as aircraft enterprise's material-selection cases. Such design can avoid the major disadvantage of WITS [34], i.e. there is no server-side database to store historical data. Moreover, a Bulletin Board System (BBS) is employed to help collect data so as to enhance knowledge acquisition function and system improvement.

II. SYSTEM ARCHITECTURE

The proposed system aims at helping aircraft designer select suitable and reasonable material for airframe, providing knowledge for inexperienced engineer and accumulating enterprise-level material-selection expertise.

Screening and ranking are two vital steps in material-selection process [1]:

(1) There are thousands of materials and processes available. Screening materials can eliminate materials that cannot meet the material selection constraints [3] while improving efficiency and accuracy;

(2) Ranking materials is to evaluate the comprehensive performance of the candidate materials and provide the best suitable material.

Thus, the proposed system combines screening and ranking methods. In this way it can not only make use of expertise, but also bring more standardization into material-selection process.

Furthermore, screening materials is an unstructured decision-making process. This process requires the support of heuristic experience or specific examples of material selection. Here expert system theory is the solution. In this paper, the screening function is implemented through a material screening module based on expert system theory.

Material ranking provides designer with sole material-selection result and it is a structural decision-making process. The designer can employ MCDM theory to select the most suitable material from candidates. In this paper, the ranking function is implemented through a material ranking module based on MCDM theory.

Fig. 1 shows architecture of the proposed system. The proposed system has three basic modules:

(1) Material screening module: To transfer design requirements into material-selection requirements and provide qualitative material-selection results;

(2) Material ranking module: To evaluate and rank the comprehensive performance of candidate materials so as to provide the most suitable material-selection result;

(3) Database supporting module: To gain material

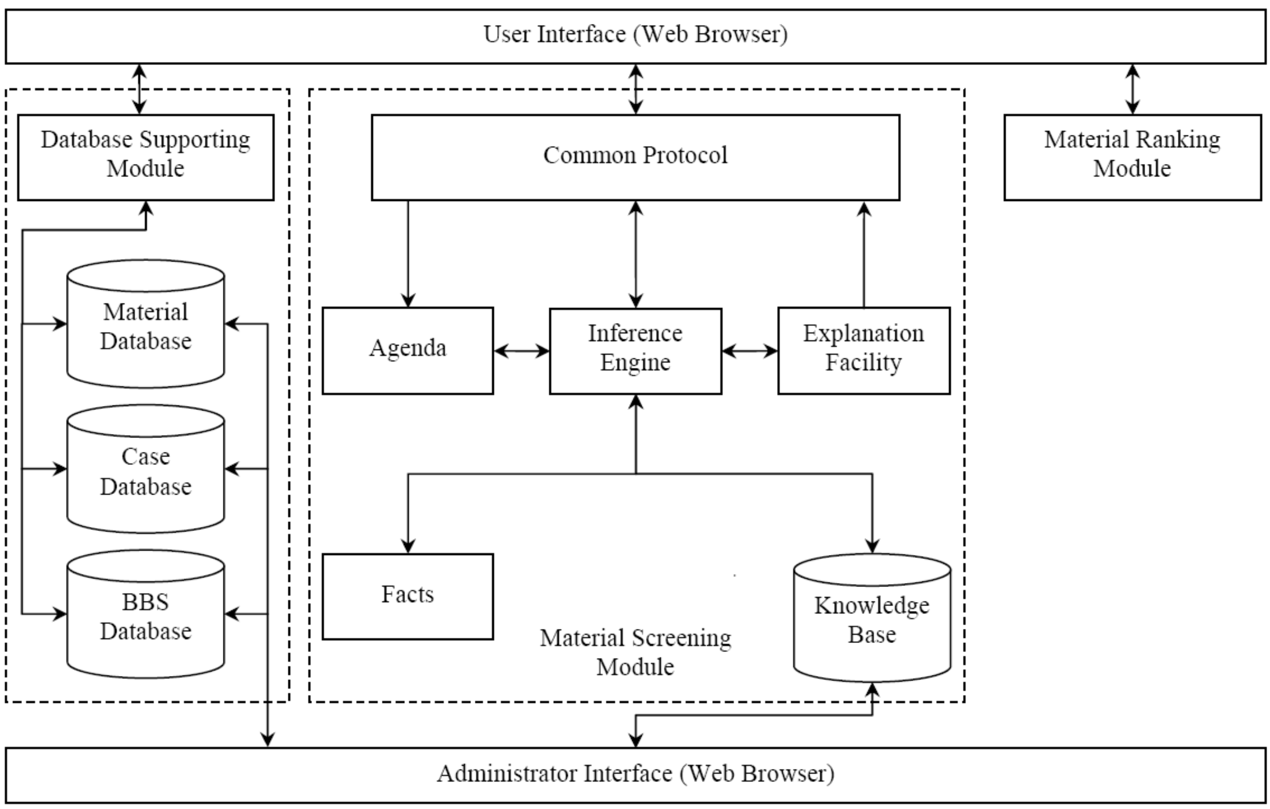

Figure 1. Architecture of the web-based computer-aided material-selection system for aircraft design.

property data —which are indispensable for material selection [3] — from material database; to store user's historical data in case database; and to help collect data to enhance knowledge acquisition function and improve the system according to user's feedback stored in BBS database.

The proposed system is supposed to be operated by Chinese user with web browser conveniently.

III. SYSTEM IMPLEMENTATION

This section provides implementation details of the proposed system.

A. Material screening module

(1) Knowledge acquisition

Knowledge acquisition is realized in ways of text analysis, case analysis, questionnaire survey and interview.

Material-selection rule is input into knowledge base through knowledge base management interface, which is part of the administrator interface.

(2) Knowledge present

The expertise of material selection is expressed in IF-THEN rules [34], which appear to be a natural way of modeling how expert select materials in airframe design.

(3) Inference engine and explanation facility

CLIPS is used to implement inference function and explanation facility. CLIPS, which was designed using the C programming language at NASA/ Johnson Space Center with the specific purpose of providing high portability, low cost and easy integration with external, is a popular rule-based system development tool [34]. The openness feature makes it easy to transfers traditional expert system into a web-based one.

(4) Common protocol

A common protocol is developed in JavaScript to achieve communications between user interface and CLIPS. The adoption of JavaScript is mainly attributed to the following three advantages it possesses:

- Its programs are embedded in web pages executed automatically by user's browser. User does not need to download or install them [24].
- It has no special requirement on user's computer hardware or software [24].
- It can transfer UTF-8 (Unicode) encodes into GB2312 (simplified Chinese) easily and present the rule in simplified Chinese.

B. Material ranking module

When there is more than one material in the initial material-selection result, a MCDM-based method is employed to evaluate and rank the comprehensive performance of the candidate materials and select the final result.

The ranking process involves three basic steps:

(1) Normalize the material-selection decision matrix. Since different attributes are usually measured in different units, a normalization procedure is necessary to describe these attributes in compatible units in the performance rating;

(2) Assign weights to the material-selection attributes according to the principles listed in the inference engine's output;

(3) Rank the materials. Aggregate the normalized decision matrix with the weights to obtain a value for each candidate material and rank them in descending order. The material atop the list is the final result.

For a given MCDM problem, different MCDM methods may recommend different alternatives [35]. Likewise, different normalization methods may result in different decision-making results [13,36], giving rise to a problem. In general, nobody knows the optimal selection, and so the search for the best MCDM method and the most suitable normalization method may never end [37].

In this paper, the SAW method is applied, as it can be easily computerised; the normalization method used in the VIKOR method [36] is applied, and the attribute values obtained by this method fall in the range from 0 to +1, with +1 being the best and 0 being the worst; the material selection attributes include: the static strength efficiency (σ_y/ρ, $\sigma_y^{1/2}/\rho$ or $\sigma_y^{2/3}/\rho$, where σ_y is the yield strength of the material, and ρ is the material density) [38], stiffness efficiency (E/ρ, $E^{1/2}/\rho$ or $E^{1/3}/\rho$, where E is the Young's modulus of the material) [38], material fatigue life (N_f) and material cost (C).

C. Database supporting module

(1) Material database

An aeronautical material database developed by China's Beijing Institute of Aeronautical Materials (BIAM) is employed to provide the system with data on material properties. The database includes static and fatigue mechanical testing data of over one hundred Chinese aeronautical material trademarks.

The material searching module corresponds to the data sheets in the BIAM material database and consists of three interfaces:

a. Material type and process searching interface: the user inputs the material type and process requirements, and the system outputs material sheets accordingly;

b. Material static-property searching interface: the user inputs design conditions, i.e., static strength requirements under a certain environment and working temperature, and the system outputs material static-property sheets accordingly;

c. Material fatigue-property searching interface: the user inputs design conditions according to fatigue design criteria, i.e., fatigue stress, fatigue life, stress ratio and stress concentration factor under a certain environment and working temperature, and the system outputs material fatigue-property sheets accordingly. This searching process occurs only when the desired part bears a fatigue load.

After two or three material sheets are obtained, the system establishes the intersection of these material sheets and switches to the material ranking module.

(2) Case database

The case database is structured according to features of material-selection case of aircraft design:

a. Basic information of the part: part name, component, selected material.

b. Factors considered in material selection: load type, shape, strength requirement, material strength, risk failure section, et al.

c. Strength analysis result: Load type description, strength requirement, material strength, risk failure section, et al.

(3) BBS database

Some BBS database and source files can be downloaded from the Internet for free.

D. Interface development

The system is developed by ASP.NET technology. All of the interfaces are designed in Chinese.

IV. SYSTEM INTRODUCTION

The development of this system proceeds through three stages: a feasibility study, prototype development and system maintenance.

Prototype testing and modification is an ever-improving process. For a given task that simulates actual design work in a typical aircraft primary structure material selection case, obtaining a selection result that coincides with the actual application in the real case requires successively improving and modifying the material selection rules with the help of knowledgeable engineers (system developers) and selected users (aircraft designers) until the correct result is obtained. Several typical aircraft primary structure material selection cases are used in this testing process.

System maintenance is more of an open-ended activity. Detailed tasks, including material database management and knowledge base maintenance, can be fulfilled by system developers and designated personnel.

This section introduces the system function.

A. Material screening interfaces

The user/ aircraft designer can access the system with web browsers conveniently.

Fig. 2 shows a screenshot of the inference engine interface that adopts the friendly man-machine interactive mode of question-answering.

The inference engine outputs the requirement for material selection, including material type (steel, aluminum, titanium, et al), process (plate, forging, extruded shapes, et al), design criteria and the material attributes required to rank the materials.

The explanation facility in expert system, which explains how inference engine works and why the answers are get, can enhance reliability of reasoning results.

Fig. 3 shows a screenshot of the explanation facility interface. This interface can list all of rules that have been triggered in a given material-selection case.

After the inference engine provides an output—the referential result, the system screens the material(s) off the material database accordingly.

Fig. 4 shows a screenshot of the material screening interface.

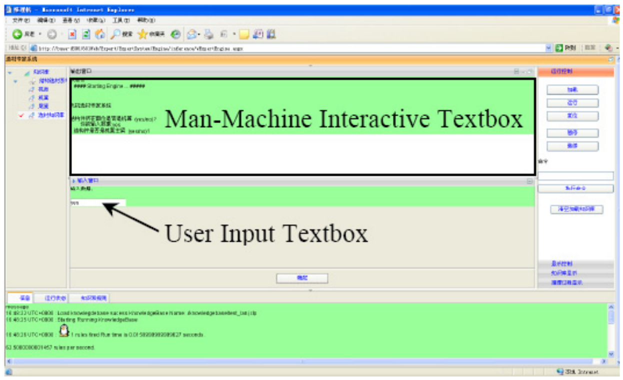

Figure 2. A screenshot of inference engine.

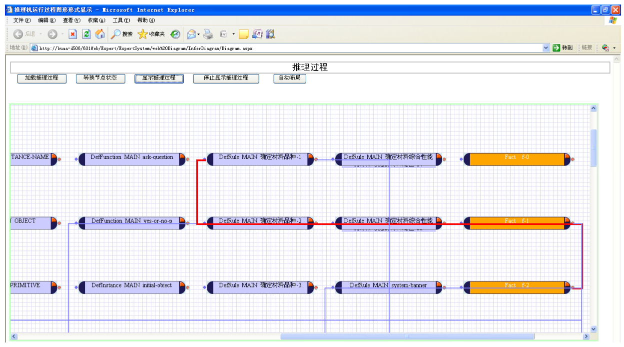

Figure 3. A screenshot of explanation facility interface.

Figure 4. A screenshot of material screening interface: query by material type and process.

B. Material ranking interface

When there is more than one kind of material in initial material-selection result, we need to employ MCDM-based method to evaluate and rank the comprehensive performance of these materials, so as to get the final result.

Fig. 5 shows a screenshot of the material ranking interface.

C. Knowledge base management interface

The system has a knowledge base management interface to update the material-selection knowledge base.

Fig. 6 shows a screenshot of the knowledge base management interface.

D. Case database management interface

Fig. 7 shows a screenshot of the case database management interface.

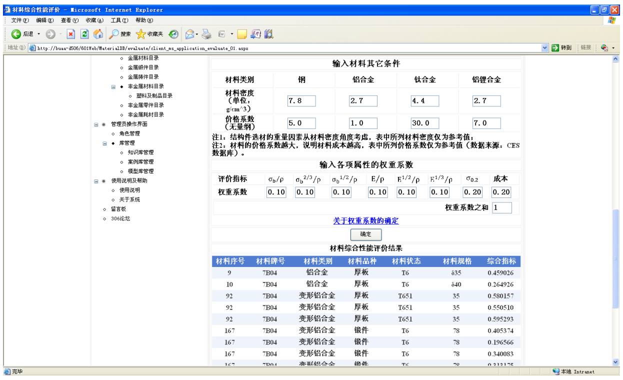

Figure 5. A screenshot of material ranking interface.

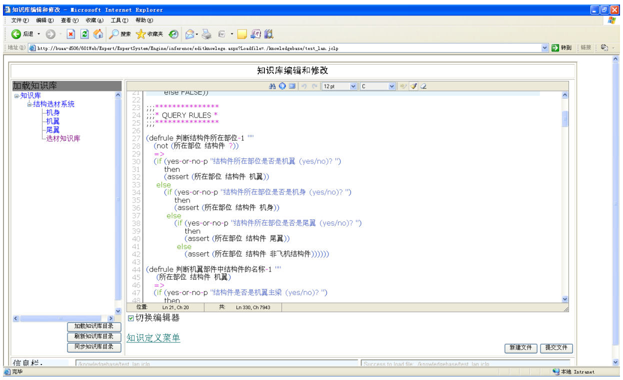

Figure 6. A screenshot of knowledge base management interface.

Figure 7. A screenshot of case database management interface.

V. SYSTEM VERIFICATION AND VALIDATION

The system was installed on user's intranet for verification and validation. Several actual material-selection cases of aircraft primary structure are used for system testing, to make sure results obtained by this system coincide with actual application in real case.

In this section, two examples of material selection for a fighter are used to illustrate the effectiveness of the proposed system. One is for the wing spar and the other is for the upper fuselage panel. These two parts are both primary structures of the aircraft.

A. Case 1: Wing spar material selection

According to past design cases in the case dabasase, the expected design conditions for this wing spar are:

a. Minimum yield strength (σ_y): 300 MPa
b. Maximum fatigue stress (σ_{max}): 150 MPa
c. Minimum fatigue life (N_f): 1.00E+06 cycles
d. Stress ratio (R): 0.5
e. Stress concentration factor (K_t): 1.0

The interaction between the inference engine and the user proceeds as follows (Q for Question, U for User):

Q: Is it a wing part? (Yes/No)
U: Yes.
Q: Is it a wing spar? (Yes/No)
U: Yes.
Q: Please select the type of static load that this part sustains: 1. tensile load; 2. compressive load; 3. bending load. (1/2/3)
U: 3.
Q: Does it sustain fatigue load? (Yes/No)
U: Yes.
Q: Does the aircraft serve in a sea atmosphere or a corrosive environment? (Yes/No)
U: No.
Q: Is its cost considered? (Yes/No)
U: Yes.
Q: Will it be manufactured in a batch? (Yes/No)
U: No.

* * * * * * Inference Output Begins * * * * * *
Component: Wing
Part Name: Wing Spar
* * * Material/Process * * *
Material Type: Steel, Aluminium or Titanium
Material Process: Forging or Plate
* * * Material Test Data Considered * * *
Whether Tensile Test Data Is Considered: Yes
Whether Fatigue Test Data Is Considered: Yes
Tensile Test Environment: Atmosphere
Tensile Test Temperature: Room Temperature
Fatigue Test Environment: Atmosphere
Fatigue Test Temperature: Room Temperature
* * * Material Selection Attributes Considered * * *
Static Strength Efficiency: [σ_y^(2/3)/ρ] (Benefit Attribute)
Stiffness Efficiency: [E^(1/2)/ρ] (Benefit Attribute)
Fatigue Performance: [N_f] (Benefit Attribute)
Economical Efficiency Index: Material Cost (Cost Attribute)
* * * * * * Inference Output Ends * * ** * *

The system then selects the material from a material database according to the user's input:

Material Type: Steel, Aluminium and Titanium
Material Process: Forging and Plate
Tensile Test Environment: Atmosphere
Tensile Test Temperature: Room Temperature
Tensile Test Grain Direction: L
Minimum Yield Strength (σ_y): 300 MPa

Fatigue Test Environment: Atmosphere
Fatigue Test Temperature: Room Temperature
Fatigue Test Grain Direction: L
Maximum Fatigue Stress (σ_{max}): 150 MPa
Minimum Fatigue Life (N_f): 1.00E+06 cycles
Stress Ratio (R): 0.5
Stress Concentration Factor (K_t): 1.0

Initial Material Selection Outcome:
7B04-T6 (δ35 plate), 2D70-T6 (forging), 7B04-T6 (forging), 7B04-T74 (forging), TC18 (die forging).

User assigns weights to the four considered material selection attributes: [$\sigma_y^{2/3}/\rho$], [$E^{1/2}/\rho$], [N_f] and Material Cost. Finally, the system ranks these five materials and presents the final outcome.

Final Material-Selection Outcome:
7B04-T6 (δ35 plate).

B. Case 2: Centre fuselage upper panel material selection

According to past aircraft design cases in the case dababase, the design of the centre fuselage upper panel does not need to follow fatigue design criteria, and the expected design conditions of the centre fuselage upper panel are:

Minimum yield strength (σ_y): 500 MPa

Interactive messages between the inference engine and the user are shown below:

Q: Is it a wing part? (Yes/No)
U: No.
Q: Is it a fuselage part? (Yes/No)
U: Yes.
Q: Is it a lower panel? (Yes/No)
U: No.
Q: Is it an upper panel? (Yes/No)
U: Yes.
Q: Please select the type of static load this part sustains: 1. tensile load; 2. compressive load; 3. bending load. (1/2/3)
U: 2.
Q: Does it sustain fatigue load? (Yes/No)
U: No.
Q: Does the aircraft serve in a sea atmosphere or corrosive environment? (Yes/No)
U: No.
Q: Is its cost considered? (Yes/No)
U: Yes.
Q: Will it be manufactured in a batch? (Yes/No)
U: No.

* * * * * * Inference Output Begins * * * * * *
Component: Fuselage
Part Name: Upper Panel
* * * Material/Process * * *
Material Type: Aluminium or Titanium
Material Process: Forging or Plate
* * * Material Test Data Considered * * *
Whether Tensile Test Data Is Considered: Yes
Whether Fatigue Test Data Is Considered: No
Tensile Test Environment: Atmosphere
Tensile Test Temperature: Room Temperature
* * * Material Selection Attributes Considered * * *
Static Strength Efficiency: [σ_y^(1/2)/ρ] (Benefit Attribute)
Stiffness Efficiency: [E^(1/3)/ρ] (Benefit Attribute)
Economical Efficiency Index: Material Cost (Cost Attribute)
* * * * * * Inference Output Ends * * ** * *

The system then selects materials from the material database according to the user's input:

Material Type: Aluminium and Titanium
Material Process: Forging and Plate
Tensile Test Environment: Atmosphere
Tensile Test Temperature: Room Temperature
Tensile Test Grain Direction: L
Minimum Yield Strength (σ_y): 500 MPa

Initial Material-Selection Outcome:
7B04-T6 (δ35 plate), 7B04-T6 (δ40 plate), TC4 M (forging), 7B04-T651 (δ35 plate), 7B04-T6 (forging), 7B04-T761 (δ55 plate), TC18 (die forging), 7B04-T651 (δ55 plate), TA anneal (δ45 plate), TC18 (die forging), TC6 M (forging), TB6 (forging).

The user assigns weights to the three considered material selection attributes: [$\sigma_y^{1/2}/\rho$], [$E^{1/3}/\rho$] and Material Cost. Finally, the system ranks these twelve materials and selects the final outcome.

Final Material-Selection Outcome:
7B04-T651 (δ35 plate).

VI. DISCUSSION

Comparing the two above cases, we can see that Case 2 presents fewer material types than Case 1, the minimum yield strength of Case 2 is larger than that of Case 1, but the number of candidate materials in the initial material selection outcome was greater in Case 2 than in Case 1. A contradictory situation like this occurs due to the inadequacy of the material fatigue properties in this material database.

This system does not contain material selection attributes like corrosion, fracture toughness and crack growth, etc., because these data are not available in the BIAM material database. New attributes will factor into the material selection process when they are added to the database.

Generally speaking, knowledge-based (or rule-based) systems for material selection tend to avoid the use of new materials [28]. However, the proposed system does not have this problem, because:

(1) The system screens materials according to their type, process, static mechanical properties and fatigue mechanical properties, and new material will not be filtered as long as it possesses excellent mechanical properties;

(2) The more types and processes the user selects when setting the material search terms, the more candidates will appear in the initial selection result. This can create a

greater possibility for new materials to be listed in the initial selection result.

VI. CONCLUSIONS

In this paper, a web-based computer-aided material-selection system for aircraft design, together with its architecture and implementation details, is put forward. Its B/S architecture can meet the current demand of concurrent engineering of aircraft design. The system's effectiveness is demonstrated by two cases of material selection for a fighter.

Maintenance of the proposed system is an endless effort. To keep the system performing ideally, the knowledge and material databases should be modified and updated constantly.

Furthermore, in a given material selection problem, the process of assigning weights to the material selection attributes is the key step in implementing the detailed design requirements of each part. It should be pointed out that the weight-assignment process in the proposed system should be improved to enable the weights to more accurately reflect the design requirements.

So human is still the key role in material selection, and the system is no more than a tool to help designer select materials. In playing their own parts, the designer and the system both need to make the best of expertise, case study, material property data and other material-selection data.

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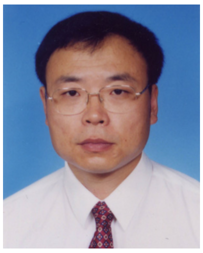

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