Materials Selection in Conceptual Design using Weighting Property Method

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Abstract:

The needs to combine selection of materials (SM) processes during the early stages of design have previously been realized. In this work, an attempt is made to ensure that there is no gap between function oriented design and the material. A methodology is being developed, for a concurrent qualitative selection of materials method (CQSM) that takes into consideration the importance of materials properties in the early design stages. The method is modified from quantitative method called weighting property method used for selecting materials in the detailed design stage. The method was modified to qualitative method; it means that the input data for materials property of the design must be qualitative data which consisting of groups or sub-groups of materials, range value properties and approximate values. By giving weight to the degree of importance of the properties, a developed database is search for the best group that can satisfy the CQSM. In the present investigation, a new numerical method has been build by using visual basic developed select materials for mechanical design in conceptual stage. This method, which is based on weighting property method (WPM) uses a new digital logic (DL) comparison with the traditional (DL) makes the result more accurate because it does not elimination problem of the least important criterion.

Keywords: materials properties data based; physical properties; materials selection; conceptual design; CQSM; DL.

طريقة الخواص الوزنية في فكرة التصميم

الخلاصة

من المهم ادراك الحاجة لدمج عملية اختيار المادة الهندسة (SM) في المراحل الاولى لعملية التصميم. في هذا البحث تم الايضاح بعدم وجود فجوة بين مرحلة الوظيفة في عملية التصميم وبين المادة الهندسية. حيث تم تطوير طريقة للاختيار هي الطريقة النوعية لاختيار المادة الهندسية المتزامن (CQSM) لتاكيد اهمية تحديد خواص المادة الهندسية في المرحلة الاولى لعملية التصميم. الطريقة التى تم تطويرها فى هذا البحث هى الطريقة الكمية لاختيار المادة الهندسية المبنية على الطريقة الوزنية للخواص والتي تستخدم في المراحل النهائية لعملية التصميم. الطريقة المعدلة تم تحويلها الى طريقة نوعية فهذا يعني ان البيانات المطلوبة لقيم الخواص للمواد الهندسية هي بيانات نوعية. حيث تم تحديد الخواص للمواد الهندسية بالمجموعات الرئيسية او الفرعية. وكذلك القيم المستخدمة هي مديات وليست قيم محددة وهي بالتالي قيم تقريبية . يتم الاختيار عن

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طريق اعطاء وزن لاهمية كل خاصية ويتم البحث عن تلك الخواص من بين البيانات الموجودة ضمن البرنامج للحصول على المجموعة المناسبة للتطبيق.
تم بناء البرنامج باستخدام الفجول بيسك . اساس الطريقة المطورة هي الطريقة الوزنية وتم تحديد اهمية الخواص واعطائها وزن باستخدام مصفوفة القرار المنطقية الرقمية وكانت محورة عن الطريقة التقليدية. وعند المقارنة بين الطريقتين وجد ان الطريقة المطورة تعطي دقة اكثر للنتائج لانها تستطيع حل مشكلة المعيار الاقل اهمية باعطائه وزنا خلافا للطريقة التقليدية التي تعطيه قيمة الصفر.

1- Introduction:

Traditionally material(s) and manufacturing process (es) selections are taken place at a detailed design stage. At this stage, the design is generally fully laid out and some parts or components drawings have already been produced. Many different methods for materials selection and design have been presented recently [1-6]. In overview of recent researches in materials selection, there were already plenty of ready-to-use materials selection methods in existence. On the contrary, there was a very little effort spent on materials identification for conceptual design. The main reason behind such an unbalanced situation may partly be due to the fact that, until present, the importance of materials identification for the early design stage has not been fully recognized by the researchers community [1].

Many approaches can be adopted to rationalize the search for suitable materials for application during early product design stage [3, 6]. These are grouping the materials into process compatible classes (since materials and processes are related), to obtain a systematic database structure. It makes the searching faster and the selection of material by "membership function modification" fuzzy logic which can be well an object fit into a defined set. Boothroyed, et al. [3] studied the problem of selecting materials during conceptual design by breaking material property values into discrete ranges. However, an alternative approach is to model such vague qualifiers as "about" and "in the neighborhood of" using aspects of fuzzy logic. Fuzzy logic relies on the concept of a membership function to determine how well an object fits into a defined set. Giachetti [7, 8] was used a fuzzy logic method to present an integrated material and manufacturing process selection procedures. This method allows the early identification of material and process alternatives. The concentrate on those alternatives have greatest potential for balancing the product's functional requirements with the economic concerns realized in manufacturing.

2- Selection Method

2.1Traditional Weighting Property Method:

In this method each material requirement or property is assigned a certain weight, depending on its importance to the performance of the part in service [9-13] as depicted in Figure (1). This method attempts to quantify how important each desired requirement is by determining a weighting factor (α), quantify how well a candidate material satisfies each requirement and determining a scaling factor (β). A weighted property value is obtained by multiplying the scaled value of the property by the weighting factor (α). The individual weighted property values of each material are then summed to give a comparative materials performance index (ℓ). The material with the highest performance index (ℓ) is considered as the optimum for the application. In cases where numerous material properties are specified and the relative importance of each property is not clear, determinations of the weighting factors (α) can be largely intuitive; which reduces the reliability of selection. This problem can be solved by adopting a systematic approach to the determination of α. Using the DL approach, evaluations are arranged in such way that only two properties are considered at a time. Every possible combination of properties or performance goals is compared and no shades of choice are required; only a yes or no decisions for each valuation. To determine the relative importance of each property or goal a table is constructed. The properties or goals are listed in the left hand column, and comparisons are made in the columns to the right [11], as shown in Table 1.

In comparing of two properties or performance goals, the more important goal is given numerical 1, the less important is given 0 and 0.5 when for the two equal important properties. The total number of possible decisions is $N = n(n - 1)/2$, where n is the number of properties or goals under consideration. A relative emphasis coefficient or weighting factor (α), for each goal is obtained by dividing the number of positive decisions for each goal into the total number of possible decisions (N). In this case, $\sum\alpha = 1$. For scaling candidate of material properties, each property is scaled, so that its highest numerical value does not exceed 100. When evaluating a list of candidate materials, one property is considered at a time. The best value in the list is rated as 100 and the others scaled proportionally. For a given property, the scaled value **β** for a given candidate material is given by equation (1).

β = (numerical value of property / max. value in the list)*100 .. (1)

For properties like cost, wear rate, weight gains in oxidation, density, etc., a lower value is more desirable. Such case, the lowest value is rated as 100 and **β** is calculated by equation (2).

β = (min. value in the list / numerical value of property)*100 …. (2)

2.2 Weighing Property Method in conceptual Design:

The methods described above are usefulness at a very early stage of product design when initial decisions on materials and manufacturing processes are made because it aims to select specific materials based on detailed material property specifications which may not be available at early stage of design process. At this stage, only general ranges of properties may have been decided upon; therefore this method has been modified for using in conceptual design stage

3. Modified the Digital Logic Approach

There exist some disadvantages in the traditional digital logic approach (TDL), the least important goal or property is given 0 in all comparisons; therefore, the positive decisions for such a goal and its relevant weighting factor would be 0. This implies that this property will be expelled from the materials selection process and does not play any role in the selection process. Therefore, the developed digital approach (DDL) is depending on the relative important of properties according to the number of properties needed for application. For example, when the application requires three properties, the relative important is divided into 3 points scale. It gives a value of 1 to the less important property, 3 to the more important one and 2 to the less important than 3 and more importance than 1. For another example, when the application required five properties, the relative important is divided into 5 points scale (Table 2). With this modified approach, the lesser important property still remains in the selection list. The Relative emphasis coefficient or weighting factor (W_i) for each property is obtained by dividing the number of positive decision for each property into the total number of possible decisions (N) (Table 3); $\sum \mathbf{Wi = 1}$

4. Development Methodology

Data Base for the Developed Digital Logic Method (DDL)

In conceptual design, the materials property data should be in general range values, for that reason, the properties are classified according to the following assumptions:

1. Data is being identified according to properties value range of sub-groups materials. Example; The Yield strength property for maraging steel is in the range of 655−2500 MPa, this it means the 655 is the minimum value of the sub-group and the 2500 is the maximum value of the sub-group.

2. All the properties in database are being classified into four levels; the range of each level is based on experience, application; these levels are: low, medium, high and ultra High.

3. According to second assumption, σ_y values for each level may give as below:-

Low strength $\longrightarrow \sigma_y \leq 250$ MPa

Medium Strength $\longrightarrow 250 \leq \sigma_y \leq 750$ MPa

High Strength $\longrightarrow 750 \leq \sigma_y \leq 1500$ MPa

Ultra-high Strength $\longrightarrow \sigma_y > 1500$ MPa

It should be mentioned that all properties are considered for compression of all material groups.

4. The levels of the properties based on four groups are calculated by dividing the limits between the maximum value for all materials to the property and the minimum value of the same property. In some properties the limits can be divided into four groups having equal ratios

S = (Max.value- Min. value)/4…….. (3)

Example; The maximum density value for the platinum is 21.5 g/cm^3 and the minimum density value is 0.77 g/cm^3 for thermoplastic; the scale is determined to be equal to $21.5 - 0.77 \backslash 4 \approx 5$ g/cm^3. Therefore, these levels may represent as follows:

- Low $\longrightarrow \rho \leq 5$ g/cm^3
- Medium $\longrightarrow 5 \leq \rho \leq 10$ g/cm^3
- High $\longrightarrow 10 \leq \rho \leq 15$ g/cm^3
- Ultra High $\longrightarrow \rho > 15$ g/cm^3

But it may also for some properties, it is not possible to divide the groups to have equal ratios; for example, the maximum and minimum melting points for metals are 3410°C and −39°C respectively (Tungsten W and Hg respectively); then the scale based on equation 3 is not scientifically accepted and the level for this property is scientifically represent as follow:-

- Low ⟶ $T_m \leq 600$ °C
- Medium ⟶ $600 \leq T_m \leq 1000$°C
- High ⟶ $1000 \leq T_m \leq 1600$°C
- Ultra High ⟶ $T_m > 1600$°C

The developed working system methodology can be defined into three phases (figure2):

Phase I

This phase begins with the designer selecting the importance of properties required for the selected application. Before comparing between properties, the designer selects the scale to each property for the required application. Then calculates the weighted factor for each property; this is because not all properties have not equal importance.

Phase II

After the system finds the subscribed materials then, the following are performed:-

1. Defining the scaled property factor ($ß_i$) to convert the normal material property value to scaled dimensionless value. This scale factor is defined for the maximum value of the materials range value property and for the minimum value for the range of the same property.

2. After defining the scale of each property value, the system calculates the weighted property index (WPI) for these properties by using the formula in equation (4).

$$\mathbf{WPI = ß_i * W_i} \quad \ldots (4)$$

In the last step of this phase, the system calculates the sum of the WPI for each property to find the material performance index (MPI) for each material by using equation (5).

$$\mathbf{MPI = \sum ß_i * W_i} \quad \ldots (5)$$

Phase III:

In this phase, the decision must be made for selecting the best candidate material. The materials are ranked according to the performance index, where the material has the highest value is the best materials for the concept design. In addition, the system plots the material performance index result of the materials as iterative chart. Figure 2 shows the flowchart procedure for the developed approach.

5. Case study

This working system methodology can be applied to known how it is worked in mechanical design such as an aircraft skin. As a first step, the performance requirements of the aircraft skin should be translated into material requirements. The desired properties of candidate material for aircraft skin is need the followings:

1. Lightness: The lighter an aircraft, the greater the range speed or payload.

2. High yield stress: The yield strength should be as high as possible for the temperature experienced by the aircraft skin in flight.

3. High fatigue strength: In flight and during take-off and landing, aircrafts are subjected to buffeting and vibratory stresses.

4. Good corrosion resistance: Failure of the material must not occur as a result of corrosion particularly taking into account that aircraft may fly in marine environment. Therefore, this property should present in any material selected (it consider as a vital property).

In the beginning, the designer must select the important properties required for the design concept by clicking on the properties required one after another and select the number related to the scale requires for the concept design (4 = ultra high, 3 = high, 2 = medium, 1= low), for mechanical properties and for density required. Regarding the selected case study (aircraft skin), the designer selects 3 for yield strength (high), 4 for fatigue strength (ultra high) and 1 for density (low) (Figures 3-5).

With these rated three properties to evaluate, the total numbers of decisions are three. Based on the DL methods, different decisions are made as shown in figures 6 and 7. The resulting weighting factors are also given in Figures 3-5. As can be seen, yield strength is given the highest weight followed by density and the least important property is fatigue strength.

The next step in the weighted properties method is to scale the properties for the candidate material. For the present application, materials with higher mechanical properties are more desirable and are considered as 100. On the other hand, lower values of density are more desirable for this application. Accordingly, the lowest values in the table were considered as 100 and other values rated in proportion according to equation (2). Figs. 8 and 9 show the results for traditional and developed digital logic methods respectively.

Figure 8 shows alpha-beta titanium alloys and aluminum alloys, series 7000 are the best. It can be seen from Fig. 9, the material performance index for the same materials are not the same. This is due to the developed digital logic method is taken in selection to calculate the weighted factors. A possible group would be the 7000 series. For a higher speed aircraft, aluminum alloys are not suitable since they do not retain good mechanical properties at the higher temperatures. The titanium alloys offer an advantage over high-strength steels which is mainly due to their lower density (about 60% that of steel). Keep in mind that after selection the preferred alloy should satisfy the corrosion criteria.

6. Conclusions

1- The detailed design stage is too late in the product development cycle to identify the constraints imposed by materials to go back and redesign the product. Clearly, the requirement is to ensure to find the design parameters associated with materials during the early stage of the design process. This is where innovation occurs and where high-level decisions on solutions, concepts, and embodiments are first made.

2- Since the materials related issues have already been addressed during the conceptual design stage, fewer iterations related to such issues should be needed during the later stages of the design. Also, the system helps the designer avoid any surprises in the materials domain unanticipated issues can easily force a designer to make non-optimal compromises or even to discard a concept altogether.

3- The Proposed method helps the designer to better identify materials related parameters before leaving the conceptual design phase. As a result when the designer leaves the conceptual design stage, the proposed design not only satisfies the prescribed functional requirements but also the materials requirements associated with the design. Additionally, the designer has a list of candidate materials that are suitable for executing the design.

4- In the present investigation, a new numerical method has been build developed select materials for mechanical design in conceptual stage. This method, which is based on weighting property method (WPM) uses a new digital logic (DL), the modified digital logic method in comparison with the traditional one makes the result more accurate because it does not elimination problem of the least important criterion.

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Table (1) Determination of relative importance of performance goals using the DL method [7]

Goal	Number of possible decision [N=n(n-1)/2] 1	2	3	4	5	6	7	8	9	10	Positive decision	Relative emphasis coefficient (α)
A	1	1	0	1							3	0.3
B	0				1	0	1				2	0.2
C		0			0			1	0		1	0.1
D			1			1		0		0	2	0.2
E				0			0		1	1	2	0.2

α = (positive decision)/N

Table (2) Relative importance of material selection factors (5-point scale)

Goal	Number of positive Decisions N=n (n-1)/2										Positive Decisions	Relative Emphasis Coefficient
	1	2	3	4	5	6	7	8	9	10		
1	5	5	5	4							19	0.287
2	4				5	5	4				18	0.272
3		2			2			1	2		7	0.1
4			1			1		2		1	5	0.075
5				5			3		4	5	17	0.257
	Total number of positive decision										66	α=1.0

Table (2) Determination of relative importance of goals using developed digital logic method

Class description	Relative importance
One attribute is extremely more important over the other	5
One attribute is least important than 5	4
One attribute is less important than 4	3
One attribute is less important than 3 and more important than 1	2
One attribute is extremely less important over the other	1

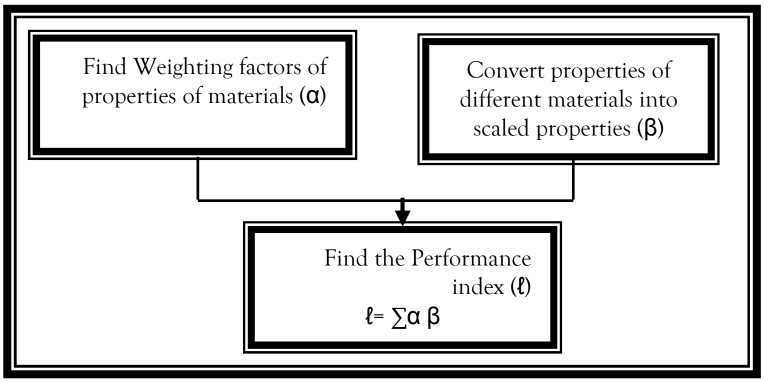


Figure (1) Weighted property method

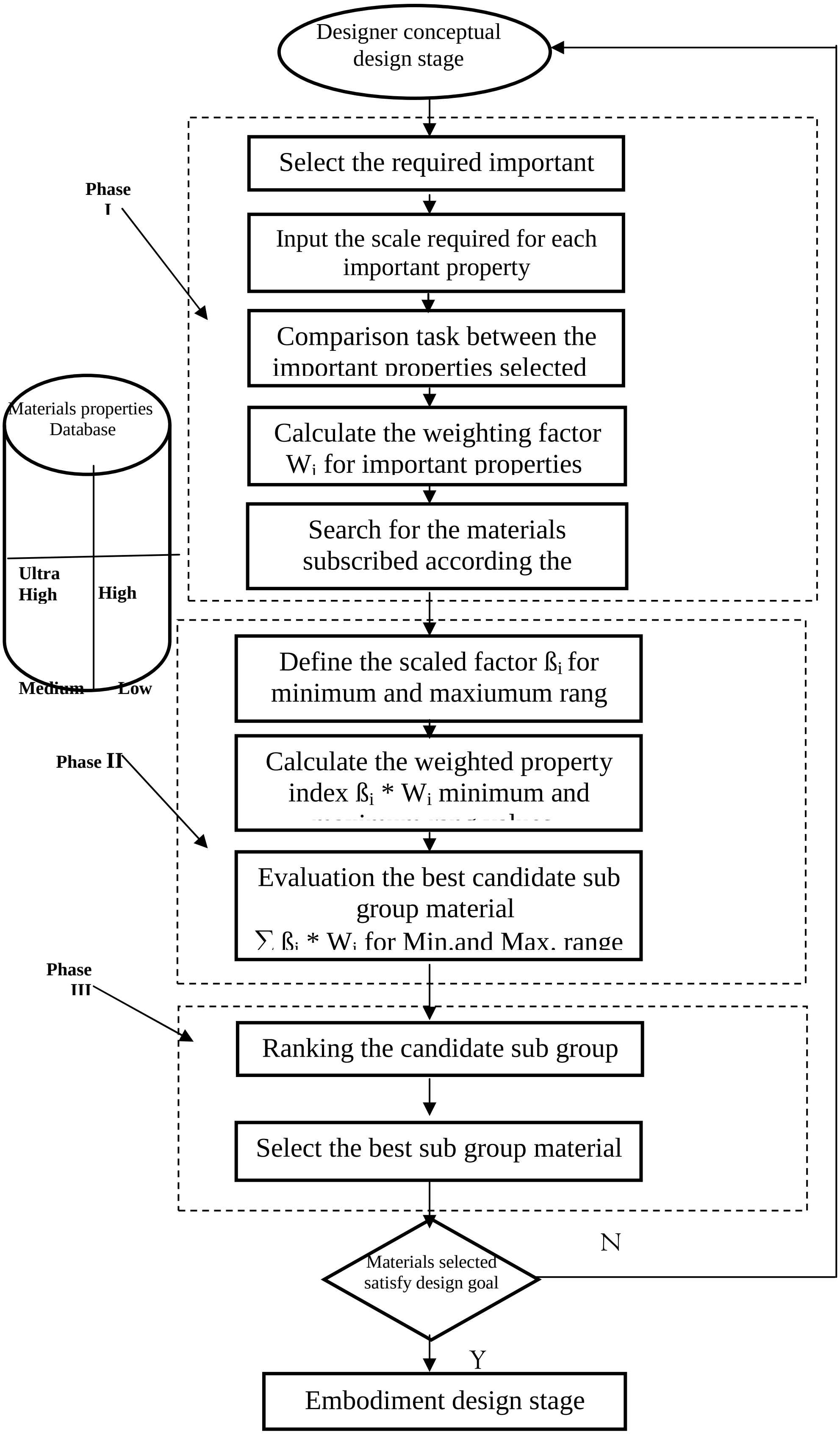


Figure (2) the flowchart illustrate the procedures of (CQSM) method

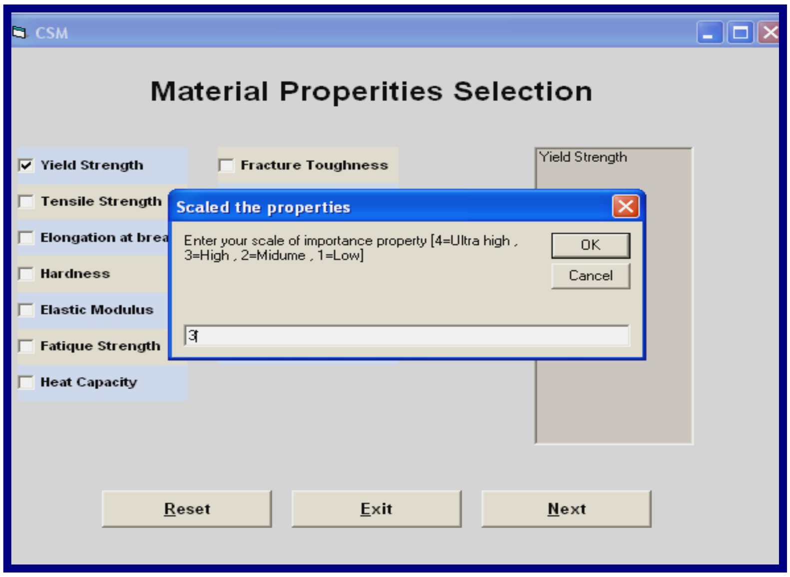


Figure (3) the material property window shows the scale
(user graph interface by visual basic).

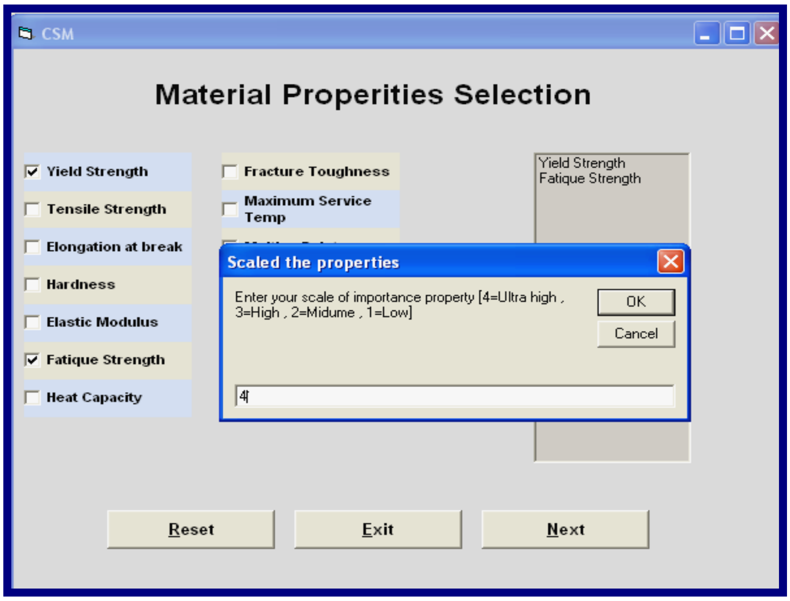


Figure (4) the material property window shows the scale
(user graph interface by visual basic).

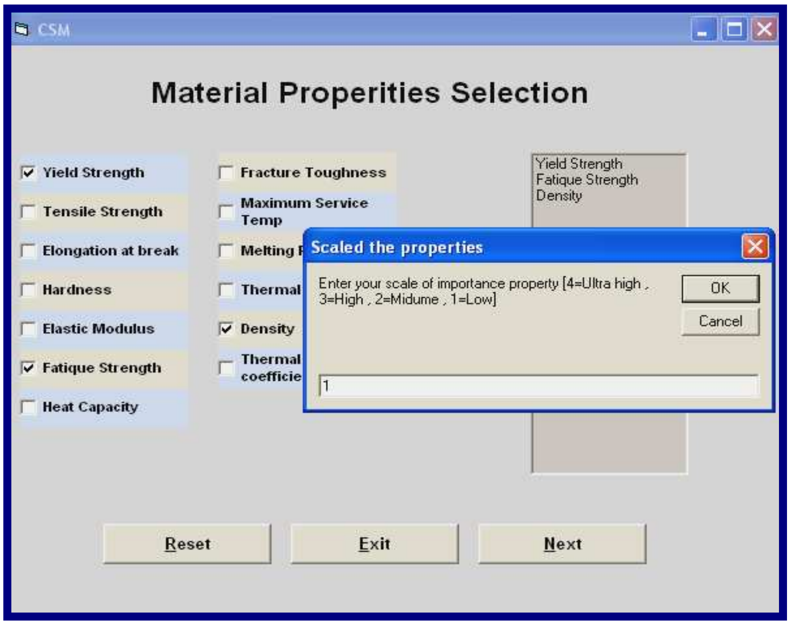


Figure (5) the material property window shows the scale (user graph interface by visual basic).

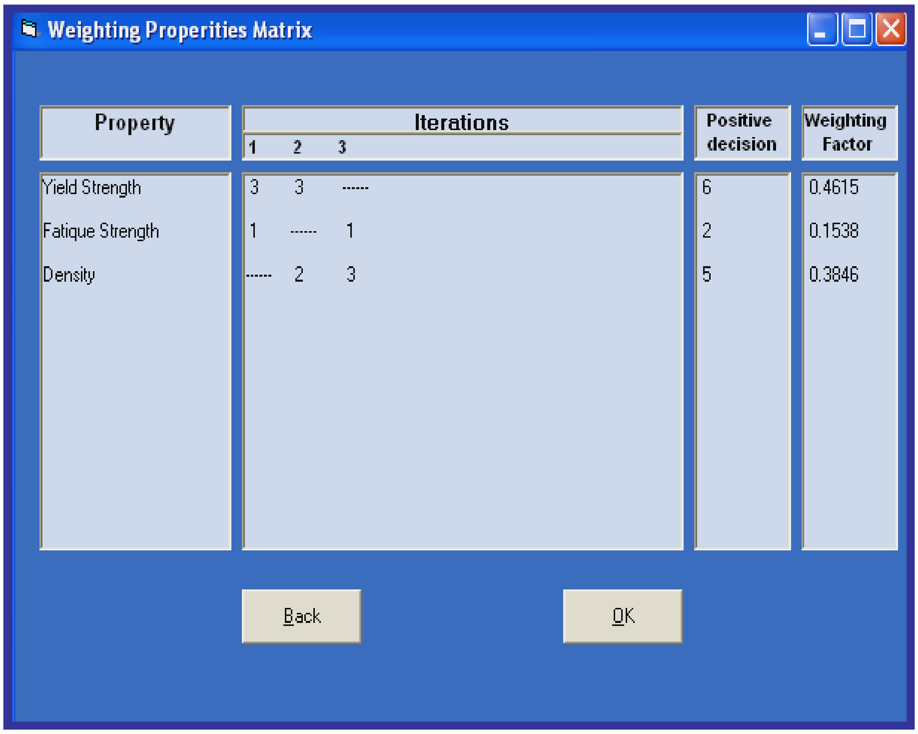
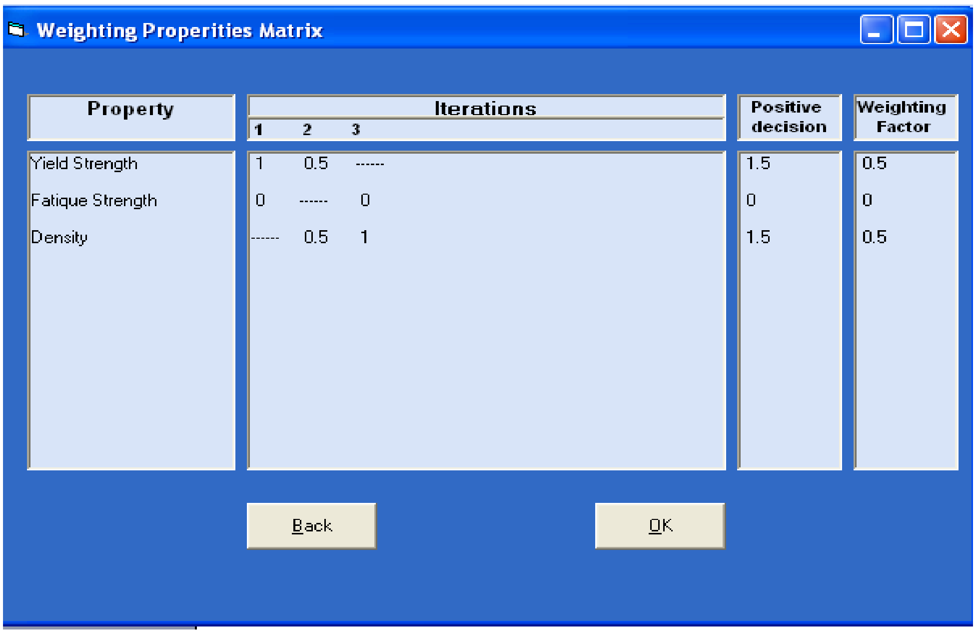
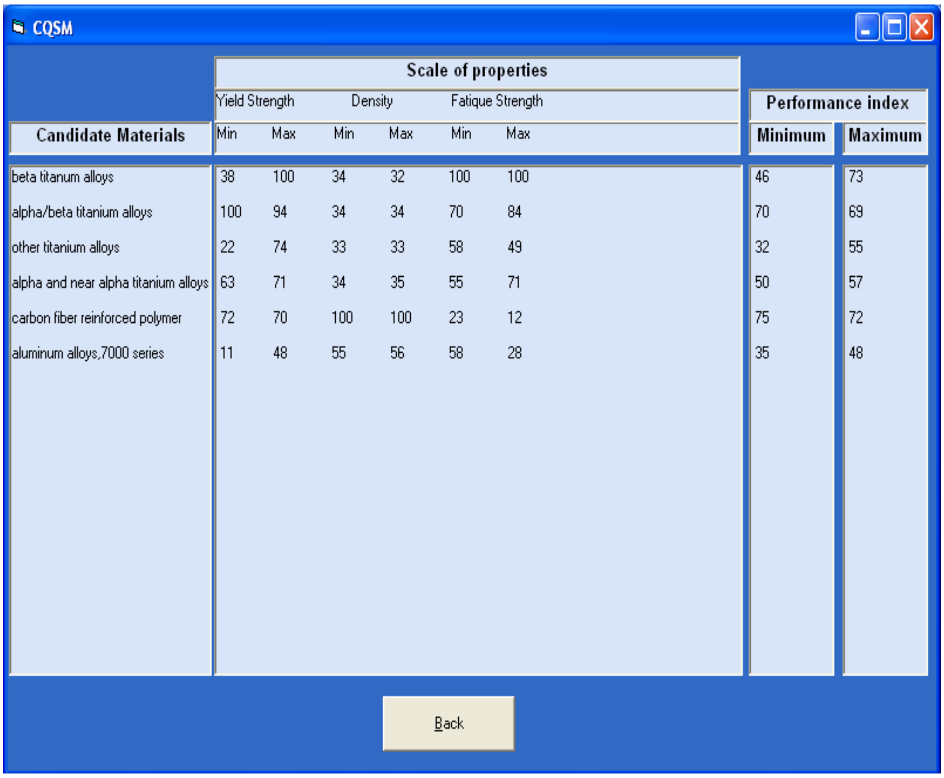


Figure (6) Weighted property matrix window using developed digital logic method (User graph interface by visual basic).



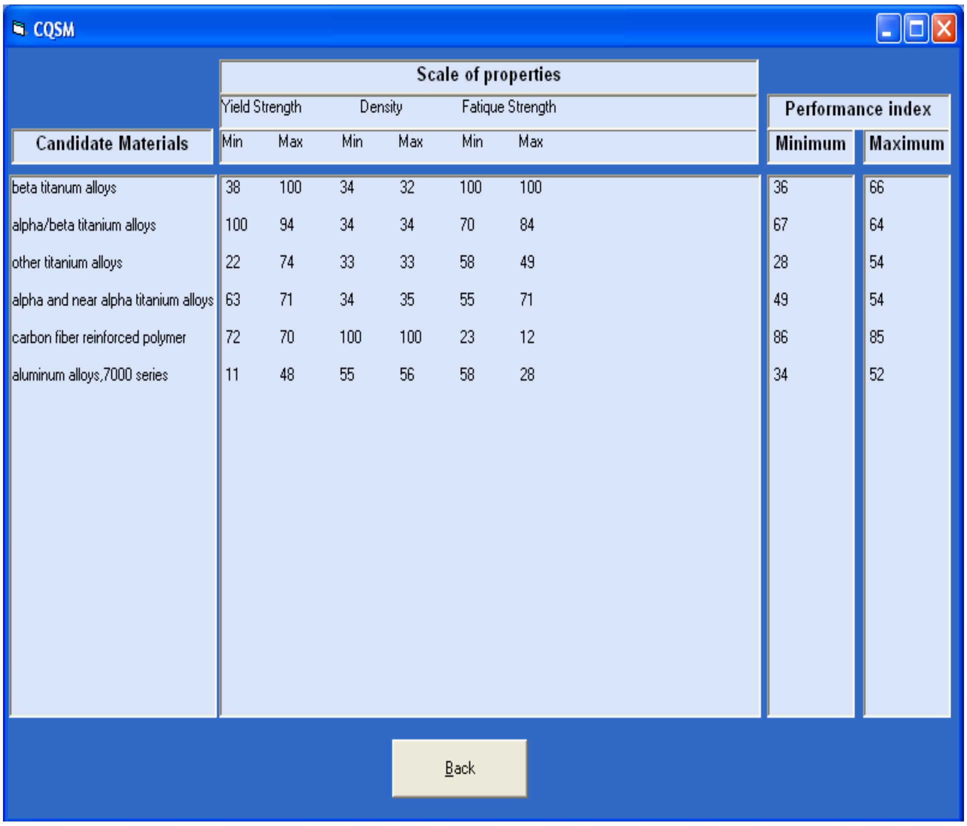
Property	Iterations 1	2	3	Positive decision	Weighting Factor
Yield Strength	1	0.5	------	1.5	0.5
Fatique Strength	0	------	0	0	0
Density	------	0.5	1	1.5	0.5

Figure (7) Weighted property matrix window using traditional digital logic method. (user graph interface by visual basic)



Candidate Materials	Scale of properties: Yield Strength Min	Max	Density Min	Max	Fatique Strength Min	Max	Performance index: Minimum	Maximum
beta titanum alloys	38	100	34	32	100	100	46	73
alpha/beta titanium alloys	100	94	34	34	70	84	70	69
other titanium alloys	22	74	33	33	58	49	32	55
alpha and near alpha titanium alloys	63	71	34	35	55	71	50	57
carbon fiber reinforced polymer	72	70	100	100	23	12	75	72
aluminum alloys,7000 series	11	48	55	56	58	28	35	48

Figure (8) Output results using developed digital logic method. (user graph interface by visual basic)



CQSM

Candidate Materials	Scale of properties						Performance index	
	Yield Strength		Density		Fatique Strength			
	Min	Max	Min	Max	Min	Max	Minimum	Maximum
beta titanum alloys	38	100	34	32	100	100	36	66
alpha/beta titanium alloys	100	94	34	34	70	84	67	64
other titanium alloys	22	74	33	33	58	49	28	54
alpha and near alpha titanium alloys	63	71	34	35	55	71	49	54
carbon fiber reinforced polymer	72	70	100	100	23	12	86	85
aluminum alloys,7000 series	11	48	55	56	58	28	34	52

Back

Figure (9) Output results using traditional digital logic method. (user graph interface by visual basic)