COMPUTER AIDED MATERIAL SELECTION FOR ENGINEERING APPLICATIONS

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Introduction

Engineering design highly depends on materials selection. It is very important and hard to choose from the more than 200,000 materials[1-2]. A well-designed computerized material selection system could be helpful. Engineers can make better material choices with the aid of computer-aided design technologies. Unlike a manual search, which may take days, an automated one could be finished in minutes [3].

Aim of Research

1. Build a database that contains most of the materials used in mechanical engineering as much as possible.
2. Build and design automated software for materials selection utilizing a hybrid methodology based on Ashby's performance indices for screening and optimizing alternatives. Then, rank the resulting materials using a grey relational method integrated with the entropy weight method to determine the optimal material that meets design requirements.
3. Optimization to make the selected material at the lowest cost and the lowest weight.

Material Selection Methodologies

Ashby Approach

Ashby's material selection strategy is a well-known, tried-and-true methodology within the Multi-Objective Decision Making (MODM) category uses material charts to choose the stiffest or lightest material. The performance indices are based on multiple properties, such as low-weight strength. When comparing approaches' effectiveness, Ashby's is better because various evaluation methods require experience and judgment, while Ashby's doesn't. The engineer must calculate weight factors to evaluate the candidate materials. Using the appropriate design formula is enough for the Ashby material methodology. Furthermore, the material indices for all materials are accurate. The Ashby technique eliminates uncertainty by performing a quantitative evaluation to determine the material index [4-5].

Material Selection Methodologies

The entropy weighted method

One of the most difficult tasks in MCDM challenges is appropriately assigning weights to the criteria based on which the alternatives have to be ranked. Calculating the criterion weights by the entropy method enables more reliable results by using objective weightings instead of subjectively weighted criteria; such criteria are categorized according to experts' opinions, which makes it hard to clarify value judgments [6-8].

Entropy weighted method

The weight determination procedure is outlined below:

Step 1: is the normalization of the decision matrix (performance indices) as follows:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^{n} x_{ij}}, i = 1,2, \dots, n; j = 1,2, \dots, m$$

Step 2: compute the entropy of each index [22].

$$e_j = -\frac{\sum_{i=1}^{n} p_{ij}\, lnp_{ij}}{\ln n}$$

Step 3: calculate the objective weight value:

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{m}(1 - e_j)}, j = 1,2, \dots, m$$

Material Selection Methodologies

Grey Relational Method

GRA is a method of analysis that determines the relationship between the design sequence and the ideal sequence. It's a good choice for determining the optimal process parameter by evaluating several alternatives and ranking them. When compared to the outcomes of conventional approaches, the GRA is able to generate dependable solutions in an accurate manner. Additionally, it also provides a better correlation between alternatives [9-11].

Grey relational analysis

The steps of classical grey relational analysis are as follows:

1- grey relational sequence generation

The grey relational sequence is formed by normalizing the decision matrix and producing the attribute comparability sequence, where the decision matrix has m alternatives and n attributes, as shown below.

$$X = (x_{ij})_{n*m}, i = 1,2, \dots, n; j, 1,2, \dots, m$$

Grey relational analysis

The dimensions and magnitudes of the indices are usually different. As a result, the indices can be normalized, for which the bigger, the better (or benefit attributes), as follows [11]:

$$y_{ij} = \frac{x_{ij} - min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})}, (1 \leq i \leq n, 1 \leq j \leq m)$$

Additionally, the cost attribute index can be normalized in the following way, where smaller is better [11]:

$$y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})}, (1 \leq i \leq n, 1 \leq j \leq m)$$

Grey relational analysis

2- Derivation of the reference sequence

After the grey relational sequence generation, a reference sequence, X0, with values equal to 1, was defined and compared to the generated sequence. The option with the highest degree of similarity was the better alternative. The following is the reference sequence [11]:

$$X0 = (x01, x02, \ldots, x0j, \ldots, x0n) = (1,1, \ldots, 1 \ldots, 1)$$

The matrix can be written as:

$$Z = (z_{ij})_{n*m} = \left|x_{0j} - x_{ij}\right|, (1 \leq i \leq n, 1 \leq j \leq m)$$

Grey relational analysis

3- Calculating the Grey Relational Coefficient

Grey relational coefficient shows the degree of grey relation between the reference sequence and experiment sequence can be computed using the equations below [11]:

$$\xi_{ij} = \frac{\text{minmin}\{z_{ij}\} + \rho \max max \{z_{ij}\}}{z_{ij} + \rho\text{max}\max\{z_{ij}\}}, (1 \le i \le n, 1 \le j \le m)$$

Where ξ_{ij} is the grey relational coefficient of the jth index to the ith alternative.

The factor ρ ∈ [0, 1] is the distinguishing coefficient and is usually set to 0.5.

Grey relational analysis

4- Grey relational grade

Grey relational grade is the numerical similarity measure between reference and comparability sequences. The grey relational grade is distributed between zero and one and obtained using the formula below, where n is the number of process responses:

$$\Gamma\,(x_0, x_i) = \sum_{j=1}^{n} W_j\ \xi_{ij}$$

Where W_j is the weight assigned to the attribute j. The total weight assigned to the attributes is unity.

Methodology of building the (CA-MC) system

The systematic methodology is implemented by generating a CA-MS (computer-aided material selector) software. An automated material selection system is being invented as a tool for industrial engineers to choose the optimal material during the product design stage. The (CA-MS) software is programmed in C# language and linked to the SQL Lite database environment, which is a quick, robust, and adaptable database management system.

The Database's Construction

The purpose of database building is to meet the needs of engineers. Material data is gathered from public sources, such as: "Materials Selection in Mechanical Design" by M. F. Ashby; "Fundamentals of Material Science and Engineering" by W.D. Callister. and efficiently displayed to developers working on a design. General information, such as material name and mechanical and physical properties, is effectively displayed on the screen. Changes and updates are uploaded in the existing format, and values are saved during database development. Two databases have been created as part of the developed system:

a) Materials Databases.

b) Material Performance indices Databases.

The (CA-MS) system software

The main form of the (CA-MS) system software, named "Computer Aided Material Selector (CA-MA) software," consists of two modules. They are the Selection Module in two levels and the Database Module. (Figure 1) shows the main form of the software.

The (CA-MS) system software

Figure (1): the (user interface) window of the software.

LEVEL ONE

Level one is for screening materials in a database, and then the next procedure is optimization with one performance index. Screening is done using go/no-go parameters (these are minimum and maximum property values that candidate materials must meet).

Figure (2): the constraint included in level one

Level two

In level two, the materials are screened and then optimized according to multiple performance indices. The ranking procedure is done by the grey relational method based on the entropy-weighted method. The process was accomplished in two phases.

Phase1: - Identification of the Design Requirement.

The user has a couple of options. Fill in the property boxes with the required properties for the design or click "Select Material" to generate a list of candidate materials that meet the design requirements through the properties display interface, as shown in Figure (3). When proceeding in the program and pressing "calculate," the program keeps working on the material selection problem and moves on to the second stage, which shows the form for selecting the multi-performance indices.

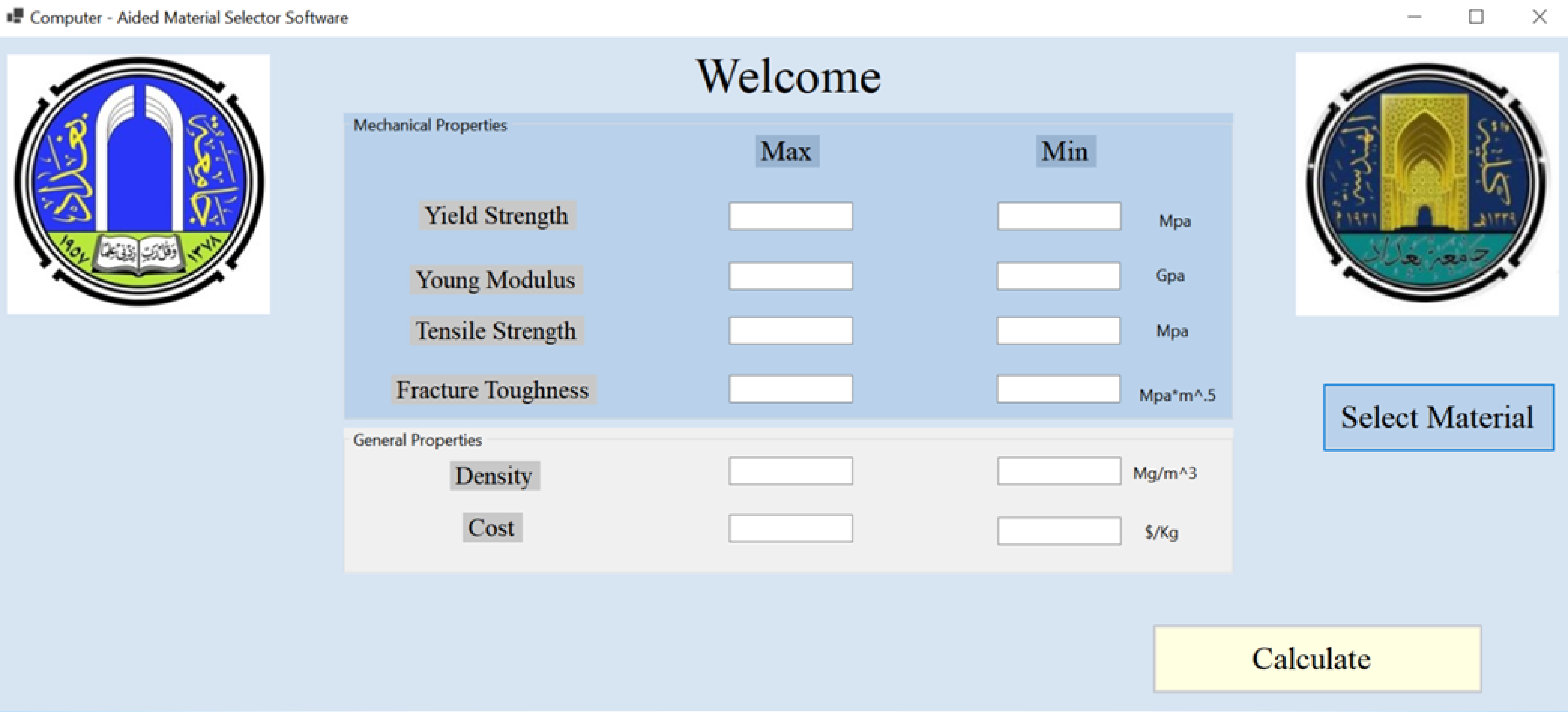


Figure (3): the design specifications window for level two.

selection Modules in the Program

Phase2: - Ranking (optimization procedure).

Through this phase, the system will assist in sorting out the remaining candidates based on optimization criteria; after clicking the "calculate" button, a new form will appear displaying the performance indices. The user can select the index required for the design by tapping the constraints button, which consists of stiffness, strength, and fracture toughness indices, followed by the load button, which consists of a tie, a beam, a shaft, and a column. User-available indices are displayed. The cost option is linked with performance indices in a separate button, which allows the user to activate or deactivate it based on the design specifications, as presented in figures (4, 5, and 6). When proceeding and pressing the "calculate" button, the data in the matrix are automatically filled from the program database, and based on the previous selection, the qualified materials are ranked in according to the grey relational analysis, and the index weight is calculated according to the entropy-weighted method. A list of optimized materials matching the design requirement is generated.

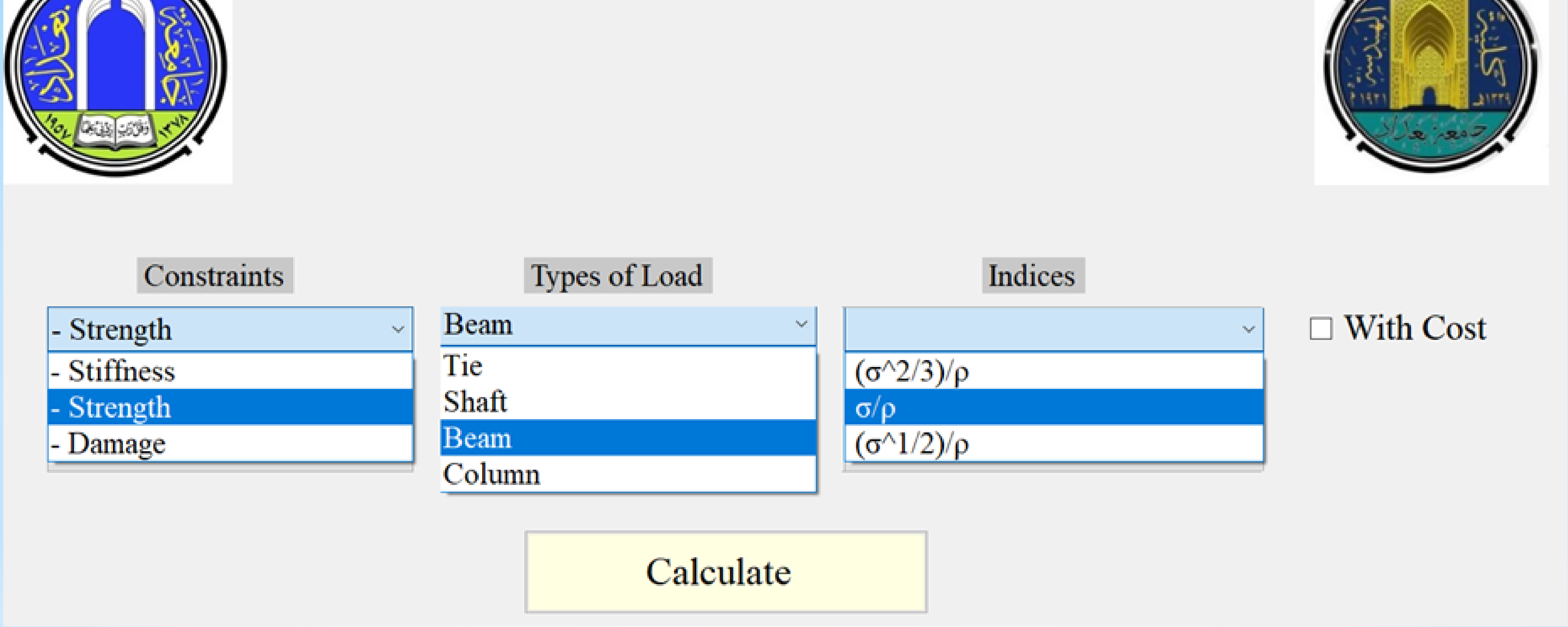


Figure (4): multi-indices selection for level two

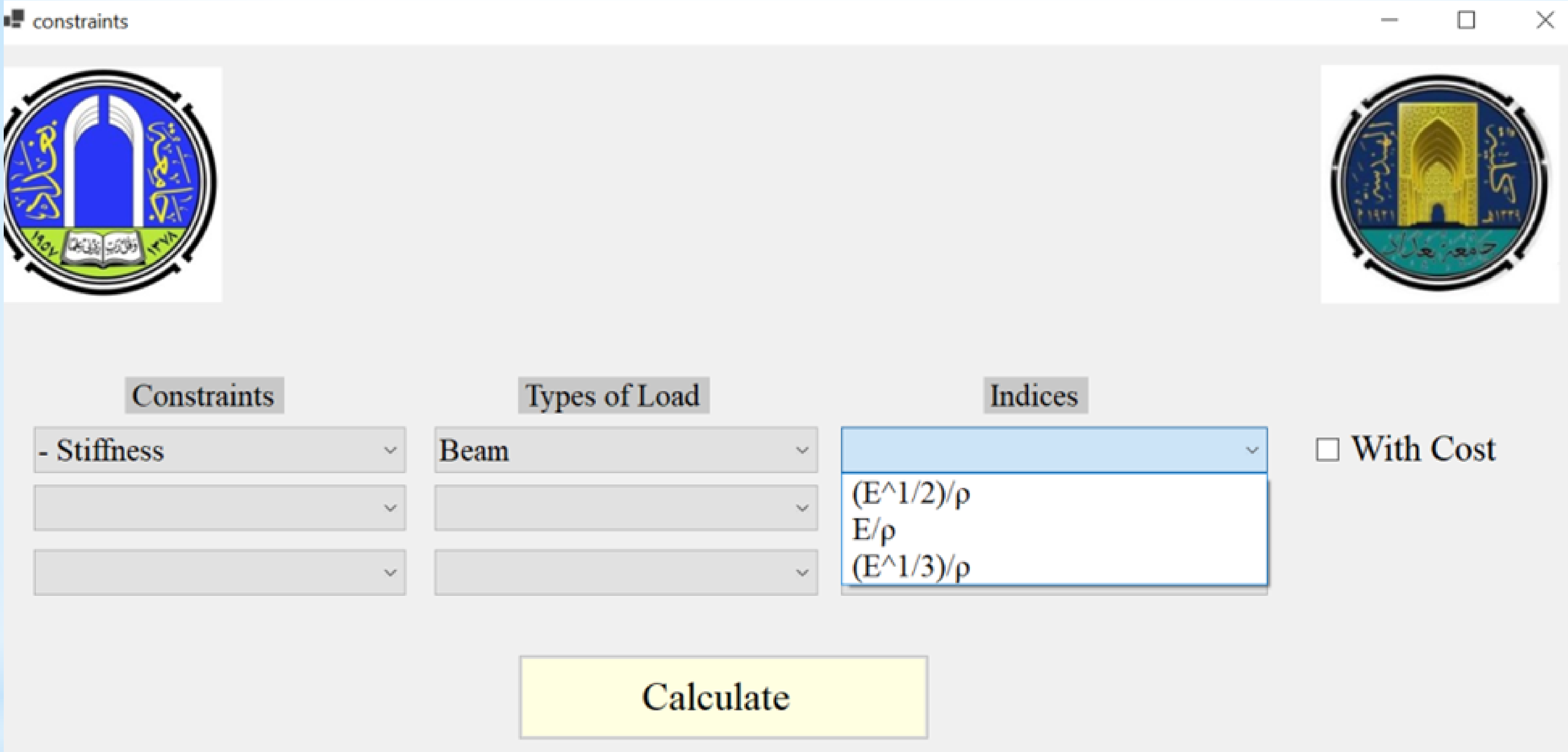


Figure (5): stiffness indices available in the software

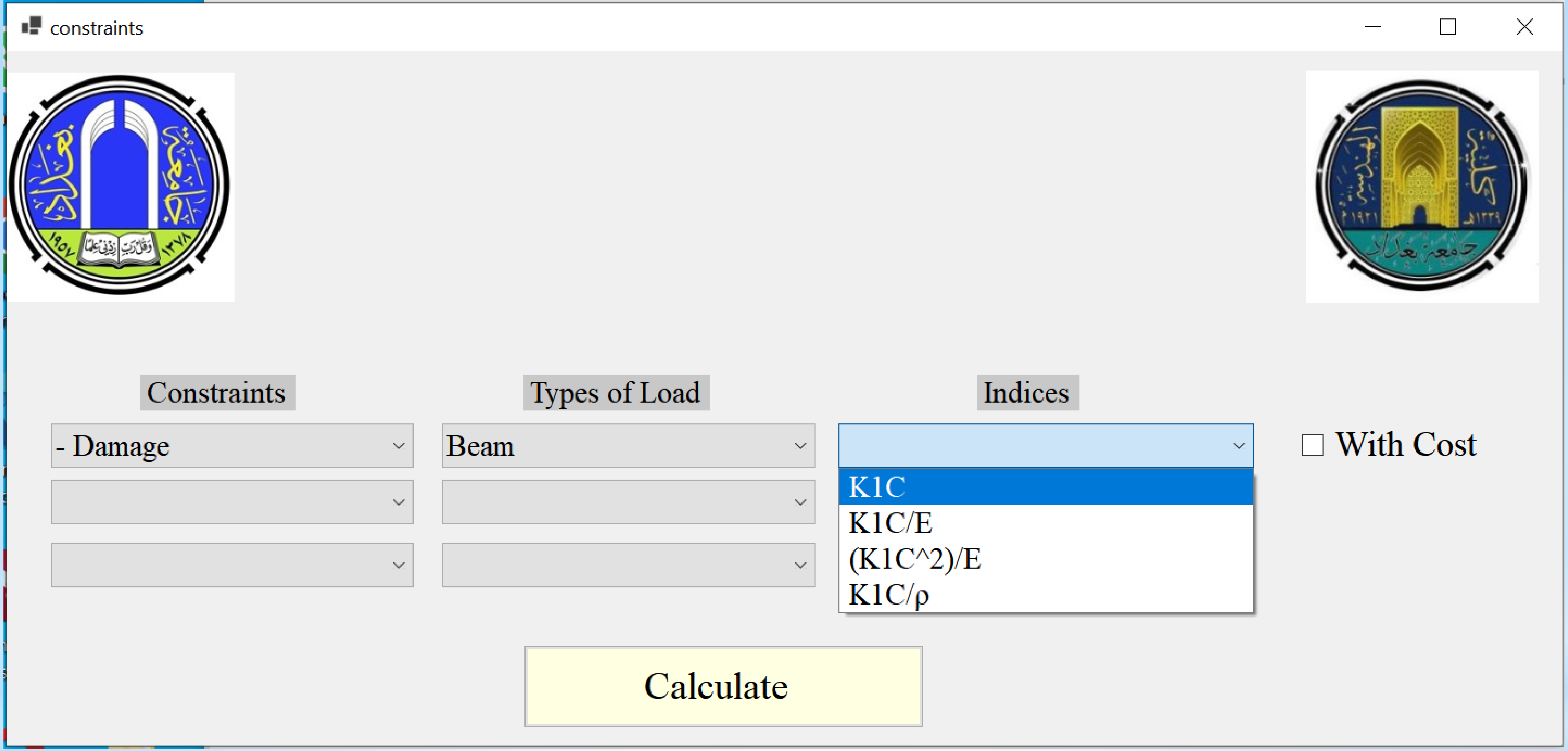


Figure (6): damage(fracture toughness) indices available in the software

Database Module

The database module is developed to edit and add new material by the user. The database is necessary to load updated information into the system or remove unnecessary data. Otherwise, the program will lose its reliability after a certain time. Users can upload their material data into the database. This section allows the user to add new information to all property tables and delete existing data the database form is shown in Figure (7).

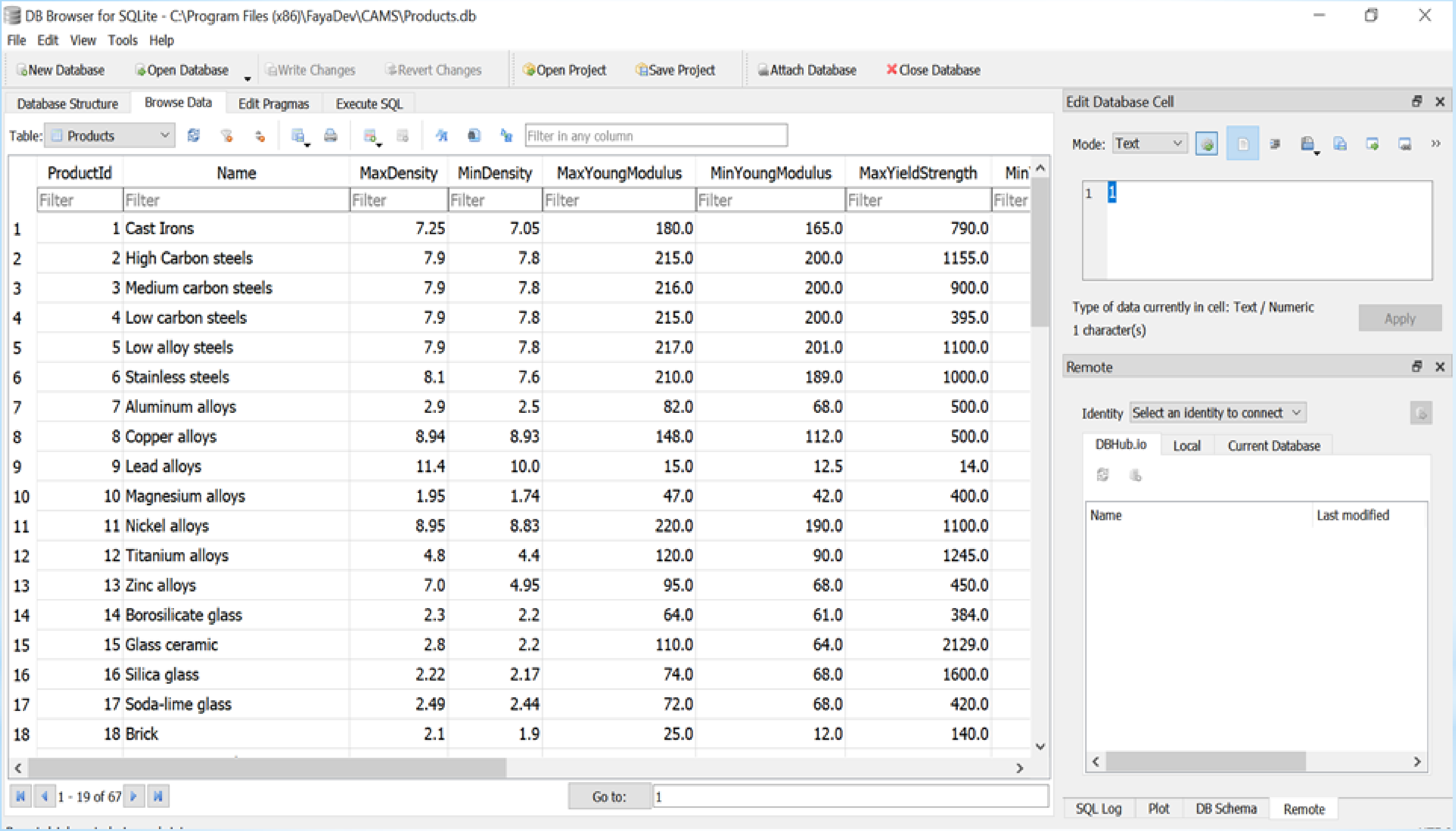


Figure (7): the database form

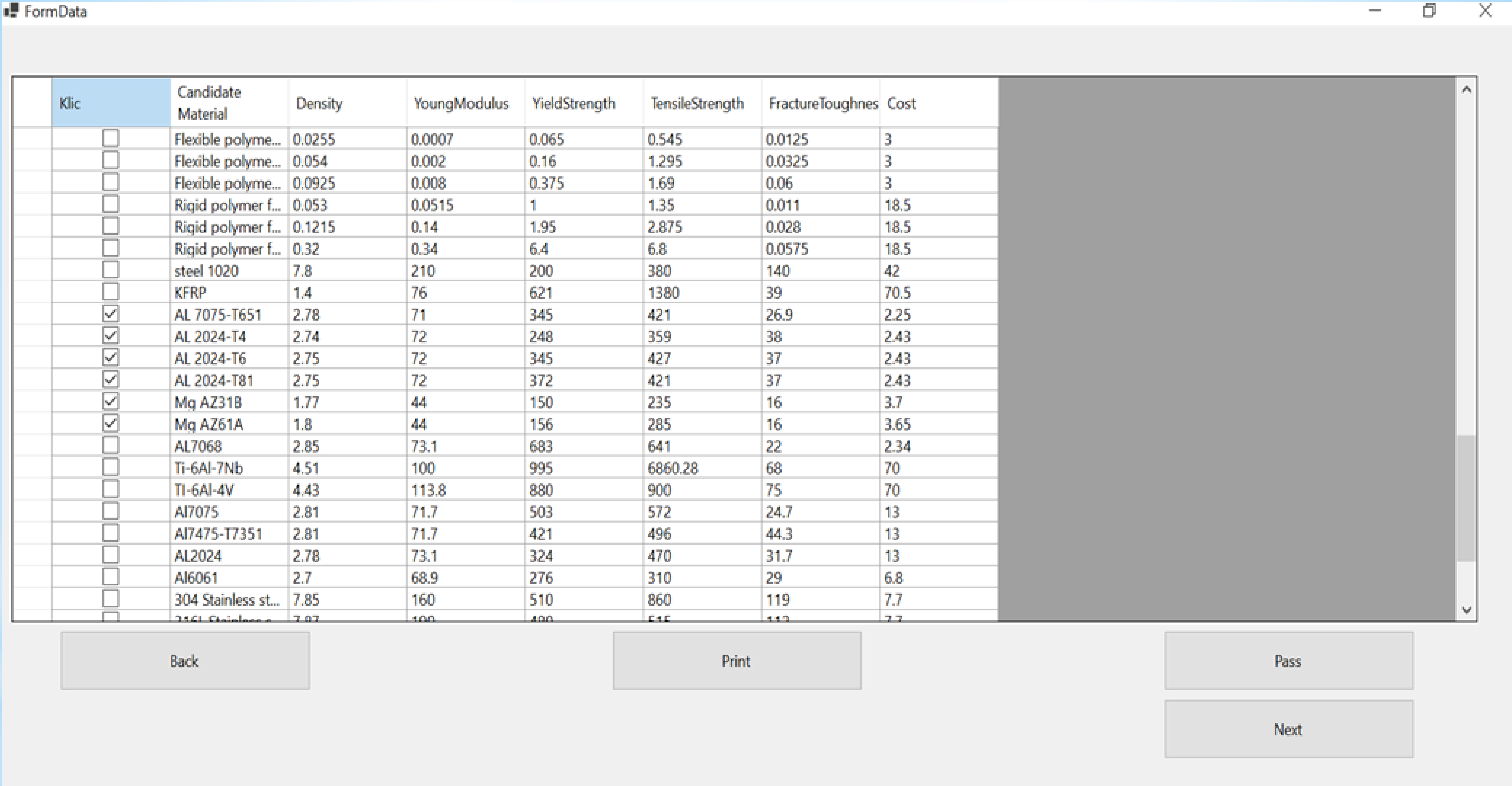
Verifications case study

Materials Selection for Lightweight Aircraft Metallic Structures [4]

The researcher developed a method for selecting materials to design lightweight metallic aircraft structures, adapted Ashby's strategy for creating a new materials selection method by computing relevant design indices and ranking materials according to the indices' values, and compared it with the AHP and TOPSSIS methods. The design requirement for lightweight aircraft metallic structures is to minimize weight, improve mechanical properties, and reduce cost. Material density, yield strength, tensile strength, Young's modulus, fracture toughness, and cost are relevant attributes. The shortlisted materials are Al 7075-T651, Al 2024-T4, Al 2024-T6, and Al 2024-T81, and magnesium alloys AZ31B and AZ61A, all are utilized in the construction of modern lightweight aircraft.

Materials Selection for Lightweight Aircraft Metallic Structures

Initially, the level two model which is available in the main form of the program relating to the multi-index phase is selected for implementation. Tapping "Select Material" will generate a list of suggested materials. Figure (8) shows the author's short list of candidate materials for this case study. Figure (9) shows the design requirement needed for the aircraft structures.



FormData

Klic	Candidate Material	Density	YoungModulus	YieldStrength	TensileStrength	FractureToughnes	Cost
☐	Flexible polyme...	0.0255	0.0007	0.065	0.545	0.0125	3
☐	Flexible polyme...	0.054	0.002	0.16	1.295	0.0325	3
☐	Flexible polyme...	0.0925	0.008	0.375	1.69	0.06	3
☐	Rigid polymer f...	0.053	0.0515	1	1.35	0.011	18.5
☐	Rigid polymer f...	0.1215	0.14	1.95	2.875	0.028	18.5
☐	Rigid polymer f...	0.32	0.34	6.4	6.8	0.0575	18.5
☐	steel 1020	7.8	210	200	380	140	42
☐	KFRP	1.4	76	621	1380	39	70.5
☑	AL 7075-T651	2.78	71	345	421	26.9	2.25
☑	AL 2024-T4	2.74	72	248	359	38	2.43
☑	AL 2024-T6	2.75	72	345	427	37	2.43
☑	AL 2024-T81	2.75	72	372	421	37	2.43
☑	Mg AZ31B	1.77	44	150	235	16	3.7
☑	Mg AZ61A	1.8	44	156	285	16	3.65
☐	AL7068	2.85	73.1	683	641	22	2.34
☐	Ti-6Al-7Nb	4.51	100	995	6860.28	68	70
☐	TI-6Al-4V	4.43	113.8	880	900	75	70
☐	Al7075	2.81	71.7	503	572	24.7	13
☐	Al7475-T7351	2.81	71.7	421	496	44.3	13
☐	AL2024	2.78	73.1	324	470	31.7	13
☐	Al6061	2.7	68.9	276	310	29	6.8
☐	304 Stainless st...	7.85	160	510	860	119	7.7

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Figure (8): candidate materials for the aircraft structures

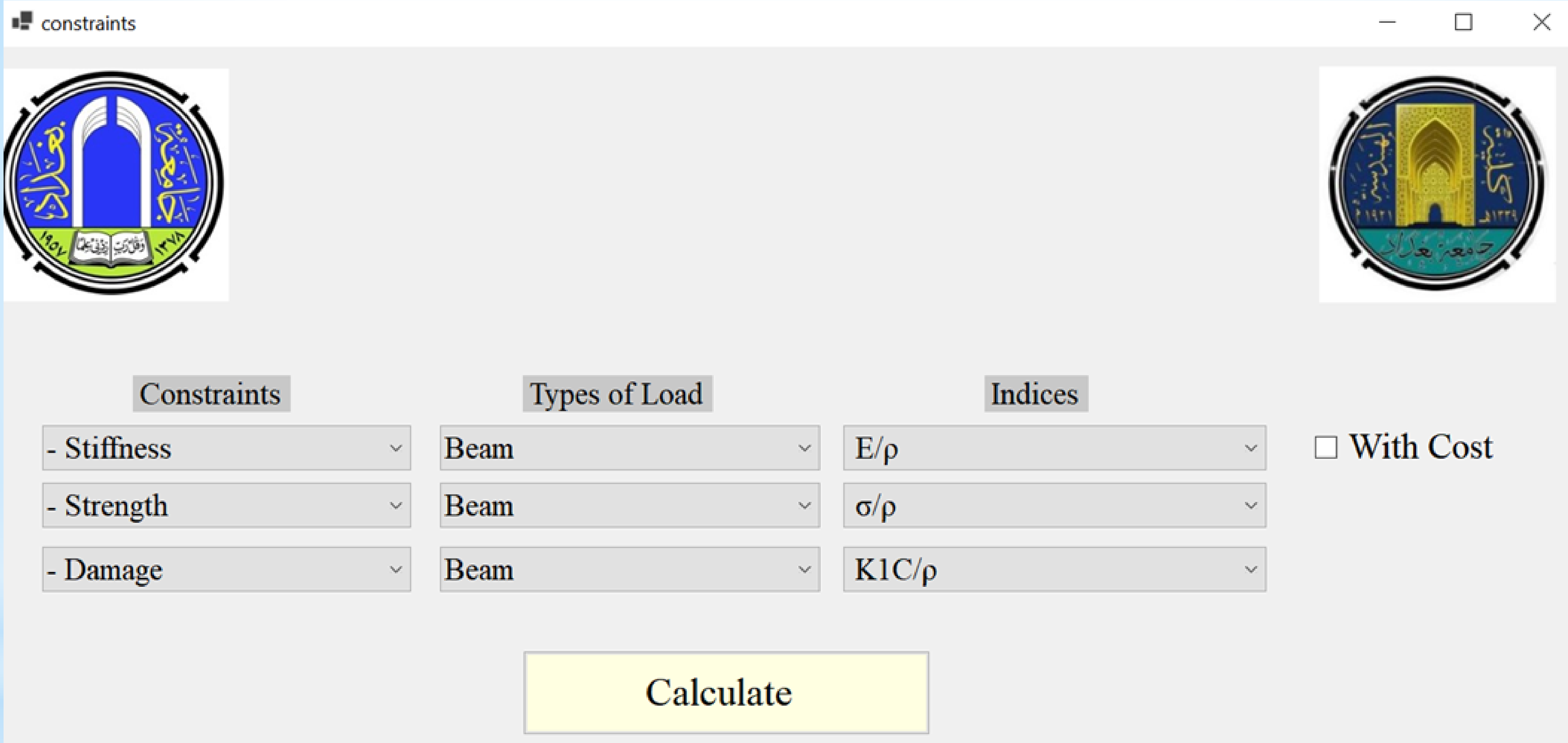

Figure (9): design requirements for the aircraft structures mData

Candidate Material	Density	YoungModulus	YieldStrength	TensileStrength	FractureToughnes	Cost	Stiffness performance	Strength performance	Damage performance	grad	rank
AL 2024-T81	2.75	72	372	421	37	2.43	26.1818	135.2727	13.4545	0.307	1
AL 2024-T6	2.75	72	345	427	37	2.43	26.1818	125.4545	13.4545	0.2761	2
AL 2024-T4	2.74	72	248	359	38	2.43	26.2774	90.5109	13.8686	0.2629	3
AL 7075-T651	2.78	71	345	421	26.9	2.25	25.5396	124.1007	9.6763	0.18	4
Mg AZ31B	1.77	44	150	235	16	3.7	24.8588	84.7458	9.0395	0.1186	5
Mg AZ61A	1.8	44	156	285	16	3.65	24.4444	86.6667	8.8889	0.1121	6

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Figure (10): the software results without cost requirement for the aircraft structures

FormData

	Candidate Material	Density	YoungModulus	YieldStrength	TensileStrength	FractureToughnes	Cost	Stiffness performance	Strength performance	Damage performance	grad	rank
▸	AL 2024-T81	2.75	72	372	421	37	2.43	10.7744	55.6678	5.5368	0.3001	1
	AL 7075-T651	2.78	71	345	421	26.9	2.25	11.3509	55.1559	4.3006	0.2795	2
	AL 2024-T6	2.75	72	345	427	37	2.43	10.7744	51.6274	5.5368	0.2786	3
	AL 2024-T4	2.74	72	248	359	38	2.43	10.8137	37.2473	5.7072	0.2542	4
	Mg AZ61A	1.8	44	156	285	16	3.65	6.6971	23.7443	2.4353	0.1117	5
	Mg AZ31B	1.77	44	150	235	16	3.7	6.7186	22.9043	2.4431	0.1113	6

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Figure (11): the software results with cost requirement for the aircraft structures

The results analysis

The author results show according to Ashby's method, based on the candidate materials, Al 2024-T81 performs the best, while magnesium alloys perform the least. "Comparing the results produced using two methodologies, AHP and TOPSIS, with Ashby's approach gives results with a certain degree of variation. In the real world, these variances are well expected. The three ranking measures used in the study agree on the optimum material, as well as the last two options are magnesium alloys, which are unsuitable for the design"[4].

The results analysis

The results of the software (our methodology) show that Al 2024-T81 is the best candidate material for its higher performance with or without cost consideration, agrees with the researcher's methodologies on the optimal material, and the last two alternatives are magnesium alloys. Table 1 shows the comparison between our results and published results.

The results analysis

Table 1: comparison between our results and published results for the aircraft structures case

	Our methodology results				researcher results[4]
	Without cost requirement		with cost requirement		with cost requirement
materials	GRAD	RANK	GRAD	RANK	RANK
AL7075-T651	0.18	4	0.2795	2	3
AL 2024-T4	0.2629	3	0.2542	4	4
AL 2024-T6	0.2761	2	0.2786	3	2
AL 2024-T81	0.307	1	0.3001	1	1
Mg AZ31B	0.1186	5	0.1113	6	6
Mg AZ61A	0.1121	6	0.1117	5	5

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