AC 2007-654: AN INTEGRATED APPROACH TO MANUFACTURING DESIGN

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An Integrated Approach to Manufacturing Design

Abstract

A major problem for students in engineering programs is the integration of materials from various course subjects. Manufacturing engineers must integrate various subject materials to produce quality products at a competitive cost. The cost is controlled not only by the design but also by the materials and processes used to obtain the desired shape of the design. A software program was developed to assist students to consider material properties, mechanical properties, and cost considerations in selecting the best material and shape to meet specific design requirements involving load and deflection restrictions for simple structures. The software is used in the basic manufacturing processes course to assist students in the evaluation of different materials and shapes to meet specific design constraints for simple structures.

Introduction

The basic manufacturing processes course in the Industrial Engineering program at the University is scheduled for the second semester of the junior year, after the students have had courses on material properties and the strength of materials. The course is required also by the mechanical engineering and the dual degree mechanical and aerospace engineering students, so it is possible to have a multi-disciplinary project. In addition to meeting the ABET requirements, it is also a good review for students taking the Fundamentals of Engineering (FE) exam. The class size ranges between 40 to 60 students in the fall semester and 85-125 students in the spring semester. The team size varies from 2-4 students, with an occasional team of 5 students.

A major purpose of the project is to integrate materials from their basic materials, strength of materials, cost estimating, and programming skills courses. For example, the students can calculate the moment of inertia, but often do not realize the impact of that upon the total cost of a basic structure. Students are first taught the basics about strength to weight ratios, which involve the ratio of the mechanical property of tensile strength to the material property of density, and the impact of these ratios upon cost. A simple problem is done manually to illustrate the calculation procedure that the software performs so that the students understand the results obtained by the model.

Need for Software Development

There are currently no software packages that follow this approach to materials selection considering design constraints and various basic structural shapes. The initial software developed[1] was based upon materials[2,3] used for teaching a basic manufacturing processes course

and for an elective in cost estimating. The only software that does relate materials to mechanical properties for design are the programs developed by Granta Design Limited[4], such as the Cambridge Engineering Selector (CES). This software has more material properties and allows the user to develop plots to assist in the selection of the appropriate material for a wide variety of situations. The CES software requires that users purchase software licenses, instruction manuals are necessary, and it takes time for the students to become competent in using the program.

The advantage of the software developed is that it gives an evaluation for all the materials considered for the specific shape selected in terms of cost, product weight, and product volume. It is limited to simple two-dimensional shapes, but the primary purpose of the program was to integrate the effect of basic design constraints, material properties, and product shape so the student could evaluate the materials based upon their cost, weight, and volume. The software developed, if marketed, would be inexpensive.

Design Problem Illustration (USA version)

A bridge is being constructed in a national park and the materials must be carried to the site as no motorized vehicles can cover the terrain. The bridge is to be 15 feet long and two beams are to provide the main supports across a deep gorge. Each beam must support a load of 4,000 lb and have a maximum deflection of 3 inches. The 4,000 load (8,000 lb total) will permit pack horses/mules to be used. Since these must be carried to the site without motorized vehicles, a maximum beam weight of 80 pounds is desired and a penalty of $1.00/lb will be charged for overweight beams. The design is flexible as to the shape of the beam and the load is initially considered to be a center concentrated load with simply supported ends. Dr. Smart has done the initial calculations on some old design data to get a rough estimate of the maximum cost and s(he) used the following data.

	Young's Modulus (E) (psi x 10^6)	Yield Strength (σ) (psi x 10^3)	Density (ρ) (lb/in^3)	Cost ($/lb)	Melting Point (K)
Steel (low C)	30	40	0.28	1	1,800
Aluminum	10	25	0.1	2	900

A sketch of the beam loading is:

The design considerations are for strength and stiffness.

4,000 lb

15'

$\delta = 3$"
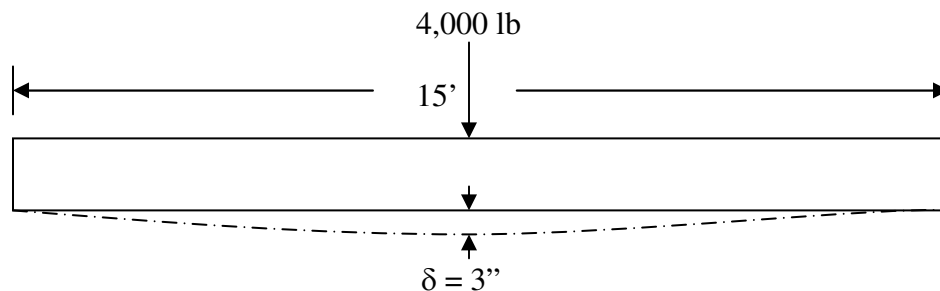
For Strength	For Stiffness	For Square Cross-section
$\sigma = Mc/I$	$\delta = PL^3/48EI$	$b = h$

Where:

$M = PL/4$	$c = h/2$	$I = (1/12)\,bh^3 = (1/12)h^4$

δ	= Maximum deflection limit (3.0 inches)
L	= Beam length (180 inches – 15 ft)
W	= Design load (4,000 lbs)
E	= Young's Modulus
σ	= Yield Strength
b	= Beam width
h	= Beam height or thickness

The total cost is the sum of the material cost, processing cost, and the cost penalty. The processing can be approximated by the expression:

$$C_p = \left(\frac{P}{A_c}\right) * \left(\frac{T_{mp}}{1,800}\right)^{0.50} * CW_f * HT_f * R_{pc} * L * A_c * N_I$$

Where:

P	= total perimeter of cross-section (in)
A_c	= cross-sectional area (in^2)
T_{mp}	= melting point of alloy (degrees K)
CW_f	= cold work factor = 1.25 if material is cold worked, otherwise use 1.0
HT_f	= heat treating factor = 1.35 if material is heat treated, otherwise use 1.0
N_I	= hollow internal section factor
	= 0.70 if material has a hollow internal section, otherwise use 1.0
L	= part length (in)
R_{pc}	= relative processing cost = 0.03 \$/in^2
P/A_c	= shape factor
$T_{mp}/1,800$	= temperature processing factor (materials with higher melting points are more difficult to process as the hot working temperatures are higher; the exponent of 0.5 was determined to be a better predictor)
L x A_c	= volume factor

Most material costs already include the factors for cold working or heat treatment. If these are in the material costs, then they do not need to be included again.

Base solution – Shape is square cross-section   therefore $I = (1/12)\,wh^3 = (1/12)\,h^4$

Deflection Constraint:
$\delta = PL^3 / 48EI = \delta = PL^3 / \{48E(h^4/12)\} = PL^3/(4Eh^4)$

Thus,

$h = (PL^3 / 4E\delta)^{1/4} = \{4000 \times 180^3 / (4 \times 3 \times E\}^{1/4} = (1944*10^6/E)^{1/4}$

Strength Constraint:

$\sigma = Mc/I = (PL/4) \times (h/2) / (h^4/12) = (3/2)PL/h^3$

Thus,

$h = (3PL/2\sigma)^{1/3} = (3 \times 4000 \times 180/2\sigma)^{1/3} = (1080 \times 10^6/\sigma)^{1/3}$

Therefore, to satisfy both the constraints,

$h = max [(1944 \times 10^6/E)^{1/4}, (1080 \times 10^6/\sigma)^{1/3}]$

For steel $E = 30 \times 10^6$ psi and $\sigma = 40 \times 10^3$ psi and thus,
$h_{steel} = max[2.83 \text{ in}, 3.00 \text{ in}] = 3.00 \text{ in}$ (yield strength is the controlling factor)

For aluminum, $E = 10 \times 10^6$ psi and $\sigma = 25 \times 10^3$ psi and thus,
$h_{Al} = max [3.73 \text{ in}, 3.5 \text{ in}] = 3.73 \text{ in}$ (elastic modulus is the controlling factor)

Cost Totals = Materials Costs + Penalty Costs + Processing Costs

Material Costs

C $= C_R \times \rho \times A \times L$

$C_{steel} = 1.0\$/\text{lb} \times 0.28 \text{ lb/in}^3 \times (3.00 \text{ in})^2 \times 180 \text{ in} = \$454$
$W_{steel} = 0.28 \text{ lb/in}^3 \times (3.00 \text{ in})^2 \times 180 \text{ in} = 454 \text{ lb}$

$C_{Al} = 2 \$/\text{lb} \times 0.10 \text{ lb/in}^3 \times (3.73 \text{ in})^2 \times 180 \text{ in} = \$501$
$W_{Al} = 0.10 \text{ lb/in}^3 \times (3.73 \text{ in})^2 \times 180 \text{ in} = 250 \text{ lb}$

Penalty Cost (for weight above 80 lbs @ 1.00 $/lb)

Steel $= (454 \text{ lb} - 80 \text{ lb}) \times 1.00 \$/\text{lb} = \$374$
Al $= (250 \text{ lb} - 80 \text{ lb}) \times 1.00 \$/\text{lb} = \$170$

Processing Costs

$$C_{p-steel} = \left(\frac{4*3.00}{3.00^2}\right)*\left(\frac{1,800}{1,800}\right)^{0.50} *1.0*1.0*0.03*180*3.00^2*1 = \$65$$

$$C_{p-Al} = \left(\frac{4*3.73}{3.73^2}\right)*\left(\frac{900}{1,800}\right)^{0.50} *1.0*1.0*0.03*180*3.73^2*1 = \$53$$

Total Cost

Steel $= 454 + 374 + 65 = \$893$
Al $= 501 + 170 + 53 = \$724$

In this case, aluminum has a large cost advantage (about 169 dollars) and other factors may dominate in the final selection, such as corrosion resistance of Al or the appearance of a smaller beam shape for steel. If the penalty costs were not included, steel would have had an advantage of approximately 35 dollars. The high penalty costs and material costs should be able to be reduced through the selection of better shapes to meet the requirements. These costs are unacceptable to the CEO and s(he) wants to know how much the costs can be lowered without decreasing the load capacity or deflection as more than three inches movement would be noticeable. That is, s(he) wants a lower cost, but equal or superior product performance. This is what is required to be competitive in the globalization environment.

The computer model gave the following values for the cost items and the differences were caused by the extra digits carried in the computer calculations.
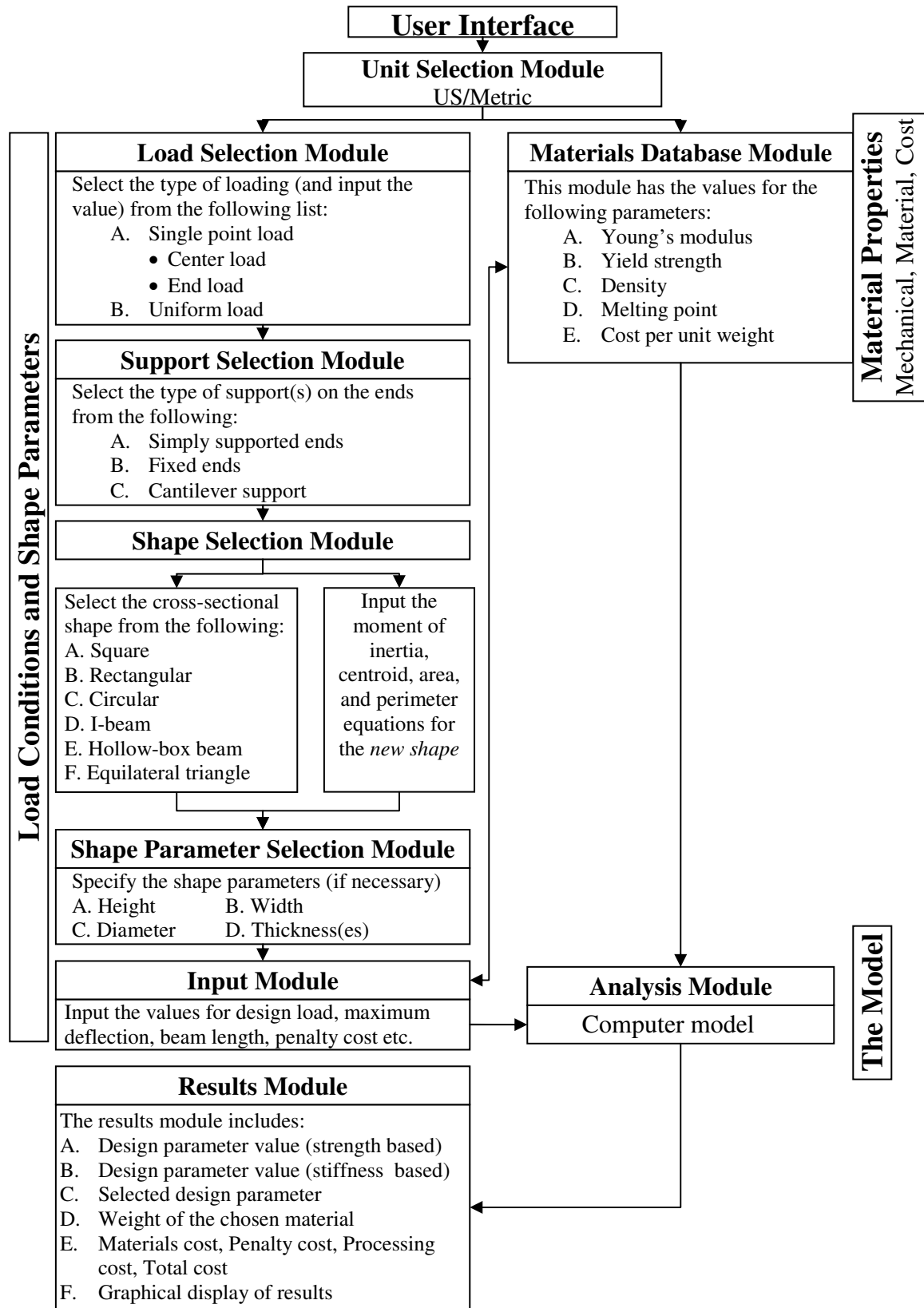
	Material Cost	Processing Cost	Penalty Cost	Total Cost
Steel	453.60	64.80	373.60	892.00
Aluminum	501.92	53.21	170.96	726.09

The students can, by selecting other design shapes and optimizing the parameters can reduce the total costs to less than $ 300. The structure weight can be reduced to less than the 80 pound goal. This helps students to realize the importance of material selection and design shape upon the total product cost. The importance of the integration of material properties, mechanical properties and cost becomes more apparent to the students. The flow chart for the computer model is given in Figure 1.

Model Logic

The computer model uses the "Goal Seek" function in Microsoft Excel® to find the solution for the design parameter. The design parameter is defined as the unknown variable in the model which, in case of a square, is the side; in case of a rectangle, is the length or width; in case of a circle, is the diameter; and so on. The initial software[1,4] developed was not able to easily solve for additional shapes and this has been added to the model to increase flexibility. The following steps are performed to find the design parameter for materials in the database.

1. Select appropriate equations for the defined load, support, and shape of the structure.
2. If all materials have been analyzed, go to Step 8; otherwise go to Step 3.
3. Add the material properties and other input parameters for the additional materials that are not in the original database.
4. Use the "Goal Seek" function to find the value of design parameter so that the given value of yield strength is almost equal to the value of expression (MC/I) using the random design parameter. By default, the value of this random variable is 0.1 and is used as the starting value in the "Goal Seek" function.
5. Using the "Goal Seek" function, find the value of design parameter so that the given value of maximum deflection is almost equal to the value of calculated deflection based on the given load and support. Once again, the starting value of the random variable in "Goal Seek" function is 0.1, but it can be changed by the user.

User Interface

Unit Selection Module
US/Metric

Load Conditions and Shape Parameters

Load Selection Module

Select the type of loading (and input the value) from the following list:
- A. Single point load
  - Center load
  - End load
- B. Uniform load

Support Selection Module

Select the type of support(s) on the ends from the following:
- A. Simply supported ends
- B. Fixed ends
- C. Cantilever support

Shape Selection Module

Select the cross-sectional shape from the following:
A. Square
B. Rectangular
C. Circular
D. I-beam
E. Hollow-box beam
F. Equilateral triangle

Input the moment of inertia, centroid, area, and perimeter equations for the *new shape*

Shape Parameter Selection Module

Specify the shape parameters (if necessary)
A. Height   B. Width
C. Diameter   D. Thickness(es)

Input Module

Input the values for design load, maximum deflection, beam length, penalty cost etc.

Materials Database Module

Material Properties
Mechanical, Material, Cost

This module has the values for the following parameters:
- A. Young's modulus
- B. Yield strength
- C. Density
- D. Melting point
- E. Cost per unit weight

Analysis Module

The Model

Computer model

Results Module

The results module includes:
A. Design parameter value (strength based)
B. Design parameter value (stiffness based)
C. Selected design parameter
D. Weight of the chosen material
E. Materials cost, Penalty cost, Processing cost, Total cost
F. Graphical display of results

Figure 1: Flow Chart of Material Evaluation Program

6. Choose the maximum value of the design variable from Steps 4 and 5 and use it to calculate the cross-sectional area, weight, and costs.
7. Go to Step 2.
8. Display the results of the analysis in tabular format with options for graphical display.(See Table 1 for the output from the model.)

Table 1: Model Results

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
3	Min	Cost Graph		Weight Graph			Go to Input Sheet			0.26079	0.89	0.59	0.00	0.85	2.24
4	Material	Young's Modulus (E)	Yield Strength (σ)	Density (ρ)	Cost	Melting Point	dm (deflection constraint)	d (strength constraint)	md (Design parameter)	Area	Material Cost	Weight	Penalty Cost	Processing Cost	Total Cost
5		(Mpsi)	(kpsi)	(lb/in³)	($/lb)	(K)	(in)	(in)	(in)	(in²)	($)	(lb)	($)	($)	($)
22	Magnesium AS91C-T6	6.50	21.00	0.066	3.00	923	0.7491	0.7703	0.7703	0.59343	1.88	0.6267	0.0133	0.99	2.88
23	Magnesium AK60A-T5	6.50	41.00	0.066	3.30	923	0.7491	0.6164	0.7491	0.56114	1.96	0.5926	0.0000	0.96	2.92
24	Aluminum 2024-T861	10.50	66.00	0.100	2.30	933	0.6643	0.5259	0.6643	0.44132	1.62	0.7061	0.0531	0.86	2.54
25	Aluminum 3003-H18	10.20	29.00	0.099	2.30	933	0.6691	0.6918	0.6918	0.47854	1.74	0.7580	0.0790	0.90	2.72
26	Aluminum 7175-T66	10.40	76.00	0.101	2.50	933	0.6659	0.5017	0.6659	0.44342	1.79	0.7166	0.0583	0.86	2.71
27	Titanium Ti-6Al-6V-2Sn	16.00	140.00	0.165	9.00	1933	0.5976	0.4093	0.5976	0.35707	8.48	0.9427	0.1713	1.20	9.85
28	Titanium Ti-13V-11Cr-3Al	16.00	160.00	0.175	9.38	1933	0.5976	0.3915	0.5976	0.35707	9.37	0.9998	0.1999	1.20	10.77
29	1015 Steel	30.00	50.00	0.285	0.60	1700	0.5107	0.5769	0.5769	0.33281	0.91	1.5176	0.4588	1.07	2.44
30	4140 Q&T Steel	30.00	252.00	0.285	0.90	1700	0.5107	0.3365	0.5107	0.26079	1.07	1.1892	0.2946	0.95	2.31
31	304 Stainless Steel	28.00	85.00	0.287	3.00	1700	0.5200	0.4834	0.5200	0.27043	3.73	1.2418	0.3209	0.96	5.01
32	Gray Cast Iron	15.00	20.00	0.258	0.55	1425	0.6078	0.7830	0.7830	0.61305	1.39	2.5307	0.9653	1.31	3.66
33	Ductile Cast Iron	30.00	50.00	0.258	0.65	1425	0.5107	0.5769	0.5769	0.33281	0.89	1.3739	0.3869	0.96	2.24
34	Steel Low C	30.00	50.00	0.280	0.80	1800	0.5107	0.5769	0.5769	0.33281	1.19	1.4910	0.4455	1.11	2.75
35	A1	10.00	35.00	0.100	2.20	900	0.6724	0.6497	0.6724	0.45213	1.59	0.7234	0.0617	0.85	2.50

Feedback Results

An evaluation form (Table 2) was given to the students in different semesters starting Spring 2005 (first time introduced into the class). In the first semester, the average feedback score was 3.70 (on a scale of 1 to 5, with 1 being "completely disagree" and 5 being "completely agree") with seven questions, 67 responses, and minimum score as 3.24. In Spring 2006, the average score went up to 3.93 based on 72 responses, 8 questions, and minimum response score as 3.69.

It may be noted that there were numerous comments in terms of adding an option to perform the analysis for a shape not available in the model, as it was one of the requirements for the project. This concern was considered and the modified program with this feature was given in the Spring 2006 semester. Other minor changes were made to make the program more user-friendly which was verified by the students comments and an increase in the feedback score from 3.78 to 4.24 (for the question "The program should be given to all future IENG 302 students since it saves time and effort in solving the project problems) and from 4.00 to 4.47 (for the questions "The program was far better than developing your own program).

Problems

One of the major problems is that some students drop the course after mid-semester and this often causes difficulty for the remaining team members. This may also eliminate the "multi-disciplinary" nature of the team project for some teams.

Table 2: IENG 302 Assessment Questionnaire for Computer Program and Project Spring 2006

To assist understanding of the interactions of material properties, mechanical properties, and product shape upon the total material cost, a computer program was developed to reduce the calculation errors in evaluating alternative shapes and materials. You were requested to evaluate one or two shapes not in the compute program to illustrate that you understood the calculation process. The following questions are asked to assess the value of the software in the evaluation of different materials, structural shapes and design parameters. Please use a scale of "1" to "5", "**1**" being "**Completely Disagree**" and "**5**" being "**Completely Agree**".

A. The program was far better than developing your own program.

① ② ③ ④ ⑤

B. The program helps in the transition, from the theory covered in related material and strength of materials courses to the practical integration of material properties, mechanical properties, section shape and cost data to improve the design of basic structures.

① ② ③ ④ ⑤

C. The program challenges the students to apply their skills and find the best material/shape for the design they are working on.

① ② ③ ④ ⑤

D. The program simplifies the sensitivity analysis and helps learn the importance of cost and design drivers in a better way than solving the problems in the class.

① ② ③ ④ ⑤

E. The program should be given to all future IENG 302 students since it saves time and effort in solving the project problems.

① ② ③ ④ ⑤

F. The program addresses issues in manufacturing engineering by providing a common platform for evaluating materials, mechanical properties, shape, design, and cost parameters analysis.

① ② ③ ④ ⑤

G. The program supports the concept of multidisciplinary team project by incorporating different parameters related to industrial engineering (cost parameters) and mechanical engineering (design parameters).

① ② ③ ④ ⑤

H. The program addresses the need for custom design software to facilitate the students in a multidisciplinary project environment.

① ② ③ ④ ⑤

Other Comments/Recommendations:

It must be noted that the final solution is dependent on the starting value of random variable used in the "Goal Seek" function. It was experienced that no single value was valid for all the problems, and in some case, can result in absurd values such as large positive or negative values. In case of absurd values, the user is recommended to change the starting value in the input sheet to a value between 0.1 and 1.0. It was noted that values as 0.1, 0.5 and 1.0 have been successful for all the problems presented thus far. One additional problem is that students do not check their answers to determine if the results are meaningful. The desired method is for them to sketch the results and view the cross-section to make certain it is logical. The problem has occurred with the I-beam problem when the students will input a large beam height/flange width ratio, such as 6, with a large I-thickness of 2 inches and flange width of 1 inch so that the flange width will be less than the I-thickness. The students were told to check the shapes of standard I-beams to determine if their results are close to standard, but few of them check their results. It is possible for the students to determine the best shape parameters for a particular shape and material, but they do not seem to have enough time and/or interest to perform these evaluations.

Summary and Conclusions

A computer program was developed to facilitate the multi-disciplinary project (an ABET requirement) in the Basic Manufacturing course in the Industrial and Management Systems Engineering department at the University. The program was well received by the students and was highly recommended to give it to the students in the future. The program not only made it possible for the students to do the project efficiently but also increased the interest of students in the project which was evident by their improved performance and higher evaluations. The software is based on Microsoft Excel® functions which is readily available to all the students and thus reduced the burden on students learning new software. The model was design in a user-friendly environment where the users can add materials to the database or analyze the shapes not available as default shapes (very useful feature that is not available in many custom software programs). It was noted that the "Goal Seek" function in Microsoft Excel® required a starting value and that could result in absurd results if inappropriate starting values are assigned. This problem was reduced by enabling the students to change the starting value if the results were not valid.

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