M-MODEL: A Mental Model based Online Homework Tool

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Abstract—**Students solve problems by developing mental models of the problem. Although these models are many and diverse, a common one used in engineering education consists of identifying the known and unknown variables, constructing a graphical problem representation, and developing a mathematical model representing the preceding steps. This is particularly the case for courses in physics, engineering mechanics, and electrical circuits. M-MODEL is a computer-based implementation of this approach to problem-solving. It requires students to build the known/unknown, graphical (free-body diagram in this paper), and mathematical models of a problem. Once the student creates a complete model, M-MODEL checks it for errors such as proper number of graphical elements, naming of variables, and equation formatting. These checks also provide students with feedback that can be used to correct or improve their models. Once students are satisfied with their models, M-MODEL proceeds to solve their equations as well as display the correct solution for them to compare to their models. M-MODEL also provides tools that individual authors can use to prepare problem models. An applied field test was carried out using M-MODEL with engineering solid mechanics students. The experimental group used M-MODEL to solve homework problems while a control group used traditional methods to solve the same problems. M-MODEL did result in a learning advantage for the experimental group.**

This paper discusses the features of M-MODEL as applied to an engineering mechanics course and considers how M-MODEL encourages students to apply mental model approaches to problem solving.

Index Terms—**Mental Models, Engineering Statics, Online Homework, Computer Based Instruction.**

I. Introduction:

Students solve problems by constructing mental representations or mental models of the problem. These models take many forms such as graphical, mathematical, flow charts, process steps, and schematics, to mention a few. According to Norman [1], these models can be contradictory, incomplete, superstitious, erroneous, and unstable, while varying in time. They also tend to be domain specific. For example, the free-body graphical model, variable listing model, and mathematical model are used throughout engineering mechanics courses.

It is the task of the educator to help students learn how to form accurate and useful mental models and apply them to knowledge domain problems. M-MODEL is a computer-based tool that was developed to assist mechanics and engineering educators with developing on-line homework problems using the mental models of the discipline in a consistent and flexible manner. This paper describes the student and problem author environments, the philosophy behind M-MODEL, some of the pedagogical methods embedded in it, and the results of an assessment of M-MODEL in a solid mechanics course.

Several engineering problem solving models or schema have been reported recently. These include the Wankat and Oreovicz [2] problem solving strategy, McMaster problem solving program of Woods [3] and Woods, et al. [4], Gray and colleague's [5] structured approach to problem solving, Mettes and associates [6] Systematic Approach to Solving Problems, and Litzinger, et al.'s [7] Integrated Problem Solving Model. The Wankat and Oreovicz strategy divides problem solving into definite steps including motivation, exploration, and reflection as well as the more common define, plan, execute, and check steps. The McMaster problem solving program uses a structure similar to that of Wankat and Oreovicz and implements it across entire curricula. Gray's structured approach emphasizes pattern-matching that starts with a small number of general equations which students reduce to fit a given situation. The Mettes problem solving schema is based upon a flow chart of problem solving steps and a constructionist approach to learning. Litzinger's integrated model emphasizes problem representation and the conversion from one representation (say problem statement) to another (say graphical).

Define, plan, and execute steps are the common thread among these various models. In engineering mechanics, these steps take the form of free-body diagram (FBD) development, listing of the given (known) and identifying (unknown) variables, creating a mathematical model consistent with the FBD, and final answer production.

The current trend in mechanics is to deemphasize the final answer production step and leave this to computational software, Gray and Costanzo [8]. Mechanics educators now tend to emphasize model building rather than rote computational procedures.

Four components are commonly used to build a mental model. These focus on the: problem statement, a graphical representation, such as a FBD, given/find information typically in the form of lists, and a system of equations that will produce the final answers. These components represent the core of engineering mechanics problem solving, have a long standing tradition in engineering mechanics, and are consistent with current trends in engineering mechanics education. To be useful to students solving a problem, these components must be integrated into an accurate and functional mental model.

The newest trend in engineering mechanics education is the application of computer technology to teach students, engage them in the learning process, and to help them understand mechanics concepts and principles. These are many and varied. They are perhaps best illustrated by the works of Gramoll [9, 10], Dollar and Stief [11], Stief and Dollar [12, 13], Philpot [14], Philpot and Hall [15], Stanley [16], and Gray and Costanzo [17] to list a few. Many of these are similar to traditional textbook presentations with exceptions such as interactive examples, audio/video lectures, homework sets with immediate feedback, virtual experiments, and interactive animations to develop conceptual understanding. This approach to learning problem solving is based upon examples and homework problem sets and is fairly traditional. Problem interactivity has been added to keep the student engaged with the problem. Hints, intelligent coaching, instantaneous feedback, and intelligent correcting have been incorporated by many of these authors. These systems primarily rely upon click-on-object, drop and drag, pair matching, multi-choice answers, and short answers (usually numerical) for student input and traversing the basic problem structure. They tend to be inflexible in that students must use notations, axis systems, vector directions, and equation ordering as prescribed by the problem designer rather than allowing students to make choices and decisions on their own.

The Andes problem solving system for classical physics developed by VanLehn, et al. [18] and implemented at the United States Naval Academy by Schultz, et al. [19] is based upon a Baysian network representation of a problem. This system allows considerable flexibility and generates solutions, immediate feedback, and help comments based upon the path traversed by the student through this network. Hence, the student who elects to use one set of notations will be coached through the problem and may produce a correct answer for that notation set just as the student who chooses to use some other notation system. This approach encourages students to think through the solution, plan their approach, and develop in-depth problem solving skills rather than charging directly and often blindly into and through the problem solution, Taraban, et.al [20]. Andes incorporates four elements into students' mental models --problem statement, graphic representation, variables lists, and mathematical model-- and requires students to develop each of these elements (graphical representation is optional). Andes includes an equation solving tool although students can also solve the equations off-line.

A research project conducted on some 330 Naval Academy students, approximately one-half of whom were in a control group, resulted in a 3% (1/3 letter grade) student performance improvement on departmental pencil and paper examinations by students who did Andes homework rather than traditional homework. Anecdotal results from Andes students (Schulze, et al. [19]) indicate that:

- students were initially reluctant to carefully define their variables
- some students ask for help on almost every step of a problem solution
- giving effective hints and help was found to be very difficult
- analysis of action logs revealed that students did not understand physics as well as might be thought.

M-MODEL utilizes the same four mental model components as Andes and requires students to fully develop their graphical, variables, and mathematical representations from the problem statement. Although most students will develop their representations in this order, it is not required and students can proceed however they deem appropriate. All student representations must be completed before a correct solution is possible. Students have complete freedom in processes like naming their variables, orienting their FBD vectors and coordinate systems, and selecting their units as they set up their solution. These choices are graded against the problem designer's expectations and final answers. M-MODEL is therefore an extremely versatile system that gives students considerable freedom in developing their problem solution and encourages them to utilize in-depth problem solving skills and high-order cognitions.

II. M-MODEL Philosophy

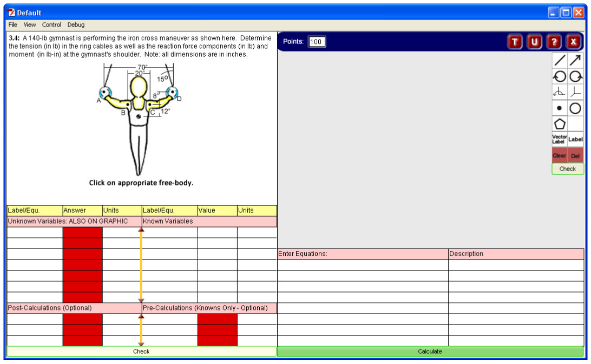
M-MODEL was conceived as a tool students can use to practice and develop their problem solving skills as well as to allow sufficient flexibility so that varied, but correct, problem solution paths are possible. This latter objective is important in that mechanics courses are typically those courses that begin the transition from well-framed problems to the more ill-defined engineering and design problems. It is also important that students learn how to formulate problems and that correct, but possibly different, answers depend upon that formulation.

M-MODEL was also designed to require students to use all four mental model components common to current problem solving practices in engineering educational literature. These mental models have a long standing tradition in engineering mechanics education and are familiar to most engineering educators. M-MODEL also focuses on the model building process and leaves the computational details to an embedded equation solver. This feature is intended to channel students away from the rush to simply write equations, substitute values, and produce answers. Rather, students must carefully build complete models before a final solution is possible.

M-MODEL also gives problem developers tools that they can use to develop their own problems and homework sets. It is also designed to reduce the task of grading student solutions. It evaluates many student mistakes and misconceptions, assigns a grade based upon mistakes and misconceptions, and records these grades when implemented on a database and active page server. The software also records student activities, sequences, and time-on-task for research and verification purposes.

III. M-MODEL Student Interface

The initial student screen is shown in Figure 1. This screen is divided into 5 different areas: problem statement, graphical representation, variables listing, pre- and post-calculations, and equation system. The problem statement is presented in the upper, left portion of the screen. Problems can contain up to two random parameters. This example contains one, the gymnast's weight. Students are encouraged to select a free-body from the problem statement diagram by clicking on the appropriate object. Students are not required to do this at the beginning, but ultimately they must select a free-body and develop a FBD. Points are deducted from a student's score and an error message appears if an incorrect free-body is selected. Students can complete their solution once the correct free-body has been selected.



3.4: A 140-lb gymnast is performing the iron cross maneuver as shown here. Determine the tension (in lb) in the ring cables as well as the reaction force components (in lb) and moment (in lb-in) at the gymnast's shoulder. Note: all dimensions are in inches.

Click on appropriate free-body.

Label/Equ.	Answer	Units	Label/Equ.	Value	Units
Unknown Variables: ALSO ON GRAPHIC			Known Variables		
Post-Calculations (Optional)			Pre-Calculations (Knowns Only - Optional)		

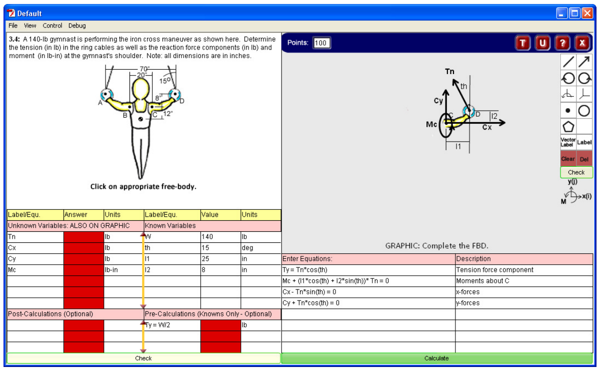
Enter Equations:	Description

Figure 1: Initial Student Interface

Once a student selects the correct free-body, it appears in the graphics representation window of the upper, right-hand screen where the student can use the tools in the toolbox to complete the FBD. These tools include: lines, arrows, clockwise and counter-clockwise moments, two- and three-dimension axis, points, circles, vector (bold) labels, plain labels, screen clearing, and object deleting. Any time a tool is selected by the student, a pop-up screen with student instructions appears. Some of the objects produced by the tools (e.g., axis and moments) can also be rotated as appropriate for the problem. Students click the "Check" button below the tool box to determine if their FBD is complete. An example of a completed FBD is shown in Figure 2.

Problem designers set the minimum number of graphical objects students must add to the FBD. This determines the detail that is expected for correctly completing a FBD. This may be as simple as 3 arrows, 1 moment symbol, and 1 two-dimensional axis for the example of Figure 2 or as complicated as shown in Figure 2 with additional lines and labels.

The graphical mental model window includes a grade display and three help buttons. Students begin with 100 points. This number is reduced whenever the student makes a mistake. This reduction depends upon the significance of the mistake. The deduction is set to be higher for a major error like selecting an incorrect free-body and less for a minor mistake like indistinct labels. The magnitude of the deducted points is at the discretion of the problem designer. The "U" button in the upper right-hand of this window activates a pop-up list of the unit symbols in M-MODEL. The "?" button activates another pop-up with an abbreviated set of instructions as a quick reference for students. Full student instructions are available in a separate file. The "T" button provides two tips to assist the student. The first is a general tip while the second is more problem specific. The second tip becomes available once the student grade falls below 90 points.



3.4: A 140-lb gymnast is performing the iron cross maneuver as shown here. Determine the tension (in lb) in the ring cables as well as the reaction force components (in lb) and moment (in lb-in) at the gymnast's shoulder. Note: all dimensions are in inches.

Click on appropriate free-body.

GRAPHIC: Complete the FBD.

Label/Equ.	Answer	Units	Label/Equ.	Value	Units
Unknown Variables: ALSO ON GRAPHIC			Known Variables		
Tn		lb	W	140	lb
Cx		lb	th	15	deg
Cy		lb	l1	25	in
Mc		lb-in	l2	8	in
Post-Calculations (Optional)			Pre-Calculations (Knowns Only - Optional)		
			Ty = W/2		lb

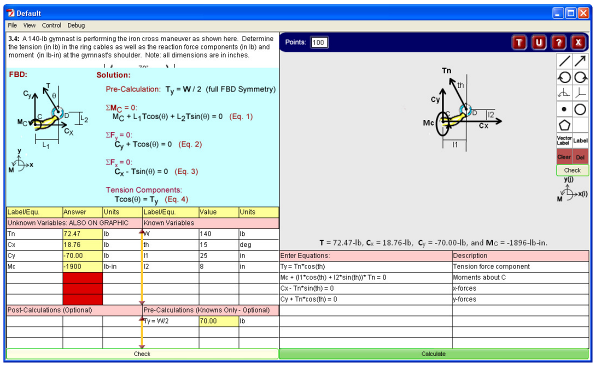
Enter Equations:	Description
Ty = Tn*cos(th)	Tension force component
Mc + (l1*cos(th) + l2*sin(th))* Tn = 0	Moments about C
Cx - Tn*sin(th) = 0	x-forces
Cy + Tn*cos(th) = 0	y-forces

Figure 2: Student screen prior to completing calculation

The left-hand side of the student interface also contains a variables list, pre-calculation, and post-calculation section in the lower quadrant as shown in Figure 2. The variables list is divided into lists of the unknown variables and known variables. These are completed by entering the labels and units for the known and unknown variables. The value of the known variables must also be entered by the student. The calculated value of the unknown variables is displayed once the student completes her model and clicks the "Calculate" button to the right. Once this "Check" button is clicked, the unknown variable labels are checked against those on the FBD (the FBD can contain more labels than those on the unknown variable list), all labels are checked to insure they are distinctly named, and all units are checked against a problem designer approved list. Error messages are displayed and points deducted if any of these errors occur. These error messages provide immediate feedback and give the student the opportunity to make corrections prior to completing the full solution.

Pre-calculation equations and units of the resulting pre-calculation variables are entered in the "Pre-Calculations" list. Only constants and known variables can be used to build the pre-calculation equations. These are entered in equation form with the pre-calculation variable label field on the left-hand side of the equation. Typical examples of pre-calculations are items like moments of inertia and areas. The pre-calculation equations are the first to be evaluated when the "Calculate" or "Check" button is clicked. The results of these equations are displayed at this time and the pre-calculation variables become available for the subsequent evaluation of the equation system in the lower, right-hand section of the student interface and the post-calculation equations. The final student screen illustrating the result of these calculations with a single pre-calculation is shown in Figure 3.

The "Post-Calculations" section is organized in the same manner as the "Pre-Calculations" section. The only difference is that post-calculations are done once the unknown variables have been determined by solving the pre-calculation and equation system equations. At this point all variables are available for the post-calculation equations and they may be evaluated. A typical example of a post-calculation is an axial stress calculated from an unknown internal force (from the "Equations" section)



3.4: A 140-lb gymnast is performing the iron cross maneuver as shown here. Determine the tension (in lb) in the ring cables as well as the reaction force components (in lb) and moment (in lb-in) at the gymnast's shoulder. Note: all dimensions are in inches.

Solution:

Pre-Calculation: $T_y = W / 2$ (full FBD Symmetry)

$\Sigma M_C = 0$:
$M_C + L_1 T\cos(\theta) + L_2 T\sin(\theta) = 0$ (Eq. 1)

$\Sigma F_y = 0$:
$C_y + T\cos(\theta) = 0$ (Eq. 2)

$\Sigma F_x = 0$:
$C_x - T\sin(\theta) = 0$ (Eq. 3)

Tension Components:
$T\cos(\theta) = T_y$ (Eq. 4)

Label/Equ.	Answer	Units	Label/Equ.	Value	Units
Unknown Variables: ALSO ON GRAPHIC			Known Variables		
Tn	72.47	lb	W	140	lb
Cx	18.76	lb	th	15	deg
Cy	-70.00	lb	l1	25	in
Mc	-1900	lb-in	l2	8	in
Post-Calculations (Optional)			Pre-Calculations (Knowns Only - Optional)		
			Ty = W/2	70.00	lb

T = 72.47-lb, **C**x = 18.76-lb, **C**y = -70.00-lb, and **M**C = -1896-lb-in.

Enter Equations:	Description
Ty = Tn*cos(th)	Tension force component
Mc + (l1*cos(th) + l2*sin(th))* Tn = 0	Moments about C
Cx - Tn*sin(th) = 0	x-forces
Cy + Tn*cos(th) = 0	y-forces

Figure 3: Final Student Screen

and section area (from the "Pre-Calculation" section).

The last section to be completed by the student prior to calculating final answers is the "Equations" section in the lower, right-hand quadrant of Figure 2. This system of equations is commonly, but not necessarily, the equations of force and moment equilibrium. This is divided into two lists: equations and comments. Comments are optional. Equation entry is intuitive and subject to very few rules.

Terms involving only constants, known variables, and pre-calculation variables are entered into these equations as appropriate. The equation solver includes the *, /, +, and – operators. The equation solver also includes the following functions: sin, cos, tan, asin, acos, atan, pow (x^y), and ln (natural logarithm). These operators and functions are used to build the terms and coefficients of the pre-calculation, post-calculation, and equation system equations.

Equations entered in this section must be independent, linear equations with the number of equations matching the number of unknown variables. Any non-linear calculations (e.g., diameter of a circle given the area) must be done in the "Pre- and Post-Calculation" sections. When the "Calculate" button is clicked, several equation format checks are done, error messages displayed, and points deducted if appropriate. The system of equations is also checked at this time to insure that they are independent. The equations system and post-calculation equations are then solved.

Next, the values of the unknown variables and post-calculation variables are compared against the correct answers generated from equations and lists supplied by the problem designer. If the problem statement includes random parameters, the problem designer must provide correct answer equations for each of the unknown and post-calculation variables that only include constants and the random variables. Student answers are considered incorrect if they are not within +/- 1% of the designer's answers. Incorrect student answers are highlighted and the student can proceed to edit any item on the screen and recalculate their answers. The student's opportunity to revise a solution based upon feedback is known to achieve deep, lasting learning (Suskie [21]).

IV. M-MODEL Authoring Tool

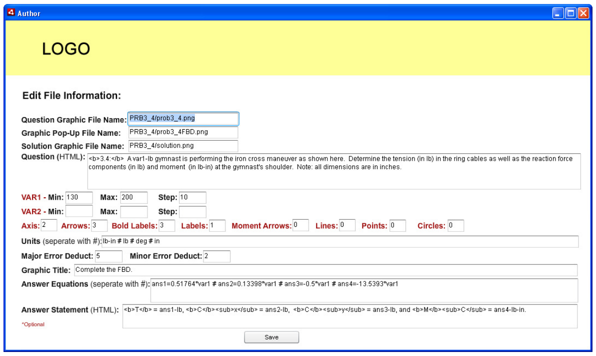
The first step in creating an M-MODEL problem is drawing the problem statement, free-body, and solution graphics shown in Figure 3. The free-body graphic is normally a copy of the problem statement graphic with all but the free-body object removed or erased. Any graphics editor that produces jpg, gif, or png graphic files can be used for this purpose. Authors save these graphic files in a folder or directory of their choice. The authoring tool shown in Fig. 4 is then be used to create a new M-MODEL problem or edit an existing problem.

The first items on this form are the names and locations of the three graphics files. The problem statement is then entered in the "Question" field using HTML-like markup tags for formatting. These tags are: <b> - bold font, <i> - italic font, <sub> - subscript, <sup> - superscript, <p> - paragraph break, and <g> - symbol font. Up to two random variables named var1 and var2 may be inserted anywhere in the question statement. The random variable minimum value, maximum value, and step size dictate the range and division of the random variables and are entered in the appropriate fields of Figure 4. The axis system (2- or 3-dimensions) is determined by entering 2 or 3, respectively, in the Axis field. The minimum acceptable number of the various graphical objects is then entered into each object's field. Acceptable units, separated by #'s, are entered in the "Units" field. Point deductions for major and minor errors are entered into their respective fields. The title for the graphic mental model panel is entered into the "Graphic Title" field. Correct answer equations for all the unknown and post-calculation variables, separated by #'s, are entered in the "Answer Equations" field. These answers are given labels, such as ans1, using standard equation notation. The equations can only use expressions involving constants and any random variables in the question statement. The correct answers statement, including any correct answers from the "Answer Equations" field, is entered in the last field. Correct answers are denoted by their label. The completed form is saved as an xml file in the same directory and with the same file name as the problem statement graphic file.

V. M-MODEL Pedagogy

M-MODEL is a non-sequential problem solving tool that encourages students to build their own problem mental models with as few restrictions as possible. Although students must complete four of the six model components (pre- and post-calculations are optional), they can be completed in any order. They can also be altered before final solution as students develop, understand, and modify their model. For example, students often add or remove variables as they are writing their equations or refining their graphic model. The cognitions underlying model development fall under the "Analyze" (breaking down material or tasks into constituent elements) and "Evaluate" (making judgments using standards and criteria), classifications of Bloom's taxonomy (Bloom [22]). Both are at the higher-order cognitions end of Bloom's taxonomy.

M-MODEL allows students to set up and solve a problem in their own terms using solution procedures of their own creation. For example, the problem of Figures 1-3 can be correctly solved by considering *Ty* a pre-calculation variable or an unknown variable. In the latter case, the



Author

LOGO

Edit File Information:

Question Graphic File Name: PRB3_4/prob3_4.png

Graphic Pop-Up File Name: PRB3_4/prob3_4FBD.png

Solution Graphic File Name: PRB3_4/solution.png

Question (HTML): <b>3.4:</b> A var1-lb gymnast is performing the iron cross maneuver as shown here. Determine the tension (in lb) in the ring cables as well as the reaction force components (in lb) and moment (in lb-in) at the gymnast's shoulder. Note: all dimensions are in inches.

VAR1 - Min: 130 Max: 200 Step: 10

VAR2 - Min: Max: Step:

Axis: 2 Arrows: 3 Bold Labels: 3 Labels: 1 Moment Arrows: 0 Lines: 0 Points: 0 Circles: 0

Units (seperate with #): lb-in # lb # deg # in

Major Error Deduct: 5 Minor Error Deduct: 2

Graphic Title: Complete the FBD.

Answer Equations (seperate with #): ans1=0.51764*var1 # ans2=0.13398*var1 # ans3=-0.5*var1 # ans4=-13.5393*var1

Answer Statement (HTML): <b>T</b> = ans1-lb, <b>C</b>_x = ans2-lb, <b>C</b>_y = ans3-lb, and <b>M</b>_C = ans4-lb-in.

*Optional

Figure 4: Problem Authors Form

student must include an additional equation in the equation section and the *Ty* label in the graphics panel. Students may also elect to not use *Ty* at all, but rather to replace it with W/2 where appropriate. Other students may elect to use some or all numerical values in lieu of variable labels and values. All of these choices will produce correct answers. Students must then "Create" (Producing alternatives or reorganizing materials in new ways) solutions which is the highest-order cognition in Bloom's taxonomy.

Although M-MODEL promotes procedural and higher-order cognitions, it is not without its penalties. First, students cannot produce correct answers without a thorough and detailed model, and often they need to refine or rebuild their model as their understanding of the problem deepens. This entails additional work on the part of the student which frequently meets with objection.

Students need to solve 2-3 problems to become comfortable with the interface. This learning curve can interfere with their learning the content material and may frustrate them. Some of this extra effort is recovered by the equations solver which saves some time. The automatic solving of the equations and lack of computational practice can be problematic during examinations if numerical answers are heavily weighted. VanLehn [18] suggests that this may not be an issue.

VI. Assessment

An experiment was conducted at the USAFA during the 2010 spring semester to measure changes in student performance attributable to M-MODEL and student attitudes about M-MODEL. This experiment involved 120 students registered in 6 sections taught by 5 instructors of a solid mechanics course. This course is taken during the fourth semester of the Mechanical Engineer/Engineering Mechanics curriculum. Three of the sections (57 students) did one-third of the required homework problems using M-MODEL and the remaining two-thirds using traditional pencil-paper methods. The other three sections only used traditional homework methods. This was done up to the first common departmental examination of the semester, approximately one-third of the semester.

Individual student grades earned on the first examination and individual GPAs were analyzed for changes in student performance. First, a linear-regression analysis of the entire population examination grades as a function of student GPA was done. This regression was then used to predict each student's examination grade given their GPA. Statistical analysis was then done on the difference between the actual examination grade and their GPA predicted grade (DELTA score). When the DELTA score is positive, the student exceeds what one would expect based on their GPA. Averages and standard deviations were then calculated for the treated and untreated students. On a 125 point scale, the treated student DELTA statistics were avg = 2.02 and stddev =11.01 and for the untreated students they were avg = -1.38 and stddev = 13.54. Treated students scored on the average about 2 points more than one might expect and the untreated students underperformed by 1.38 points. The treated group then scored 3.4 points (2.7%) better than the untreated students on the average. At the host institution, this equates to about one-third of a letter grade.

Verbal comments were also collected from the students. These can be categorized in five groups:

1. It takes time to learn the interface.
   a. M-Model version 5 addressed these comments by making the interface more intuitive.
2. It takes more time to solve homework problems this way.
   a. Embedded elapsed time data were measured. A typical problem required 10-12 minutes to complete with a grade ranging from 86% to 95%.
3. I got lost.
   a. Hints and tips have been added to address this issue.
4. M-MODEL requires too much detail.
   a. The authors can only presume that students have been missing some of the important details required to understand a problem.
5. I learned more because of feedback and opportunity to immediately correct my mistakes.
   a. Suggests a better understanding of model building in Engineering Mechanics.

Mastering the interface of early versions of M-MODEL was the biggest problem that students reported. Some students elected to go through the optional practice problem for training and some didn't. Most students had no problems with the interface after completing 2-3 problems. This is not atypical of new software interfaces. Current version 5 has addressed the majority of the issues raised by the students.

VII. Conclusions

M-MODEL is a flexible, computer-based problem solving tool based on the problem statement, graphical, given/find, pre-calculations, post-calculations, and equations mental representations of a problem. It is consistent with the model building pedagogy of current engineering mechanics education. Individual problem creators can program their own problems with minimal effort using the M-MODEL authoring tool.

Its design encourages higher-order cognitions required to bridge from linear, simple problems to more ill-defined problems on the engineering intellectual development spectrum. The flexibility of its problem solving procedure challenges students to think more deeply about problems and helps them develop the confidence they need to apply their own approach to a problem. This tool also removes the burden of computational procedures so that learners can focus upon model building which is so critical to solving mechanics and engineering problems.

A student assessment of M-Model has been conducted. This experiment demonstrated a gain in student performance on course examinations that is consistent with that measured by VanLehn [18] for physics students. Several interface issues were raised by students. These issues have been addressed in the current version 5 of M-MODEL. Interested readers may visit a demonstration version of M-MODEL at http://aln.coe.ttu.edu/anderson/m-modelv5_0/default.swf.

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