M-Model: A High-Fidelity On-Line Homework System for Engineering Mechanics

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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, construction of a graphical problem representation, and developing a mathematical model derived from the preceding steps. This is particularly the case for courses in physics, mechanics, and electrical circuits. M-MODEL is a computer-based implementation of this approach to problem-solving. It requires users 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 users with feedback that can be used to correct or improve their models. Once users are satisfied with their models, M-MODEL proceeds to solve their equations, at the instructor's discretion, as well as display the correct solution for users to compare to their models. M-MODEL also provides tools that individual authors can use to prepare problem models.

This paper discusses the features of M-MODEL as applied to a solid mechanics course. It also discusses how it may be used to encourage students to develop mental model approaches to problem solving. A student assessment of M-MODEL is also presented.

Introduction

Students solve problems by constructing mental representations the problem. These models take many forms such as graphical, mathematical, flow charts, process steps, and schematics to mention a few. As pointed out by Norman[1], these models can be contradictory, incomplete, superstitious, erroneous, and unstable, while varying in time. 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 permits engineering educators to develop problems using the principle mental models of the discipline in a consistent and flexible manner. This paper describes the user environments, the philosophy behind M-MODEL, and some of the pedagogues embedded in it.

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 Costonzo[5] structured approach to problem solving, Mettes and associates[6] Systematic Approach to Solving Problems, and Litzenger, 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 that 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).

The define, plan, and execute steps are the common thread among these various models. In mechanics disciplines, 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. As pointed out by Gray and Costanzo, the current trend in mechanics is to deemphasize the final answer production step and leave this to computational software. Four mental models are commonly used to build problem solutions. These are: problem statement, graphical representation such as a FBD, given/find representation typically in the form of lists, and a system of equations that will produce the final answers. These four mental models 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.

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[8,9], Dollar and Stief[10], Stief and Dollar[11,12], Philpot[13,14], Stanley[15], and Gray and Costanzo[16] 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. But, they rely upon click-on-object, drop and drag, pair matching, multi-choice answers, and short answers (usually numerical) for user input and traversing the basic problem structure. They tend to be somewhat inflexible in that users must use notations, axis systems, vector directions, equation ordering and etc. 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.[17] and implemented at the United States Naval Academy by Schultz, et al.[17] 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 user through this network. Hence, the user who elects to use one set of notations will be coached through the problem and produce a correct answer for that notation set just as the user 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. Andes utilizes four mental models; problem statement, graphic representation, variables lists, and mathematical model, and requires users to develop each of these mental models (graphical representation is optional). Andes includes an equation solving tool although users can also solve the equations off-line. A research project conducted on some 330 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 users (Schulze, et al.[18]) indicate that students are 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 is very difficult, and analysis of action logs reveal that students do not understand physics as well as might be thought.

M-MODEL utilizes the same four mental models as Andes and requires users to fully develop their graphical, variables, and mathematical representations from the problem statement. Although most users will develop their representations in this order, it is not required and students can proceed however they deem appropriate. But, all user representations must be completed before a correct solution is possible. Users have complete freedom in naming their variables, orienting their FBD vectors and coordinate systems, selecting their units, and etc. 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.

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 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 users to use all four mental models common to the current problem solving practices in the engineering educational literature. These mental models have a long standing tradition in engineering mechanics education and are familiar to engineering educators. M-MODEL also focuses on the model building process and leaves the computational details to an optional 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. Focusing on model building is also the current trend in engineering and engineering mechanics education.

M-MODEL is also intended to give 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 user activities, sequences, and time-on-task for research and verification purposes.

M-MODEL User Interface

The initial user 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 two, the forces $\mathbf{F}_1$ and $\mathbf{F}_2$. Users are encouraged to select a free-body from the problem statement diagram by clicking on the appropriate object. Users 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 FBD once the correct free-body has been selected with the tools on the graphical toolbox.

Once a user selects the correct free-body, it appears in the graphics representation window of the upper, right-hand screen where the user 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 user, a pop-up screen with user instructions appears. Some of the objects produced by the tools (e.g., axis and moments) can also be rotated as appropriate for the problem. Users 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 users must add to the FBD. This determines the detail that is expected for correctly completing a FBD. This may be as simple as 6-arrows, 2-moment symbols, 8-bold labels, 6-labels, and 1-two-dimensional axis for the example of Figure 2.

The graphical mental model window includes a grade display and three help buttons. Users begin with 100 points. This number is reduced whenever the user 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 "I" button activates another pop-up with an abbreviated set of instructions as a quick reference for users. Full user instructions are available in a separate file.

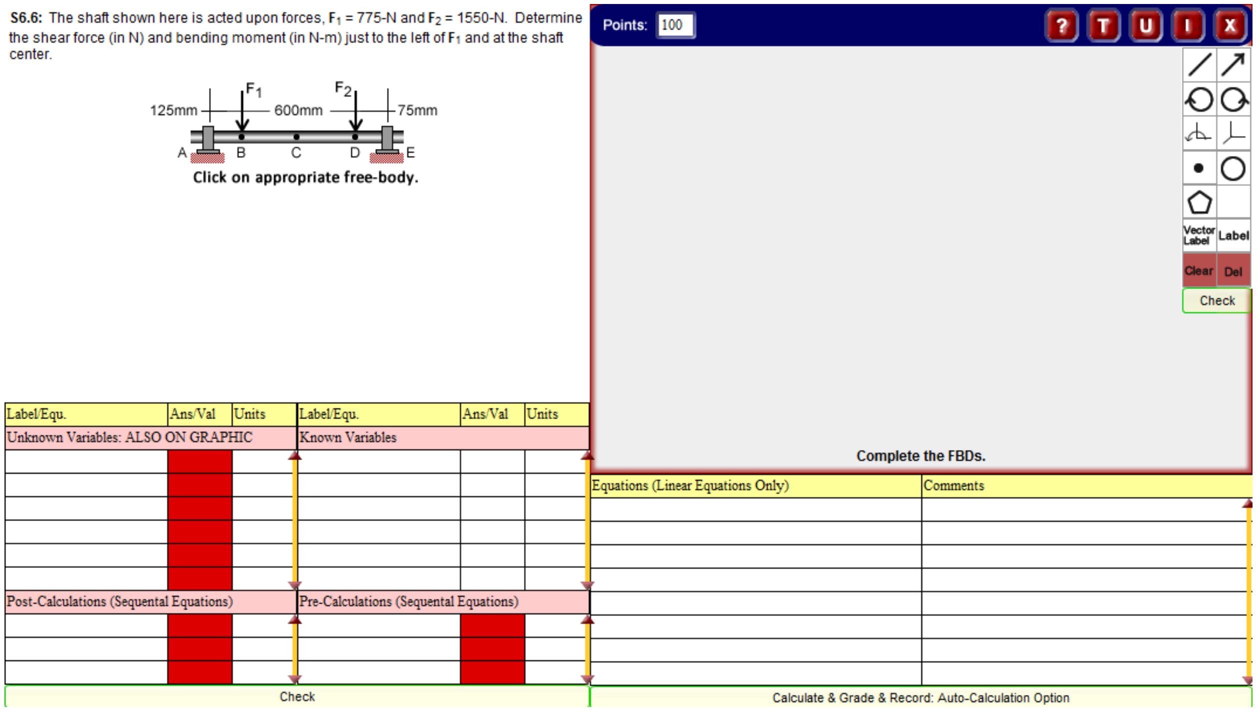

Figure 1: Initial User Interface

Two different coaches are contained in M-MODEL. The first coach is a set of problem specific tips created by the problem author. They can be individually authored or selected from a file of standard tips. A circular stack is used to display the problem specific tips. The second coach, which is accessed with the "?" button, is an intelligent tutor based upon a prioritized stack of procedural tasks. When a user requests help from the intelligent tutor, the tutor identifies where the user is in the prioritized procedure stack. If the next lowest procedure has not been done, the tutor suggests that the user proceed with that task. If it has been done, the tutor suggests that the user proceed with the highest undone task in the stack.

The left-hand side of the user 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 user. The calculated value of the unknown variables is displayed once the user 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), checks all labels to insure they are distinctly named, and checks all units for internal consistency. Error messages are displayed and points deducted if any of these errors occur. These error messages provide immediate feedback and give the user the opportunity to make corrections prior to completing the full solution.

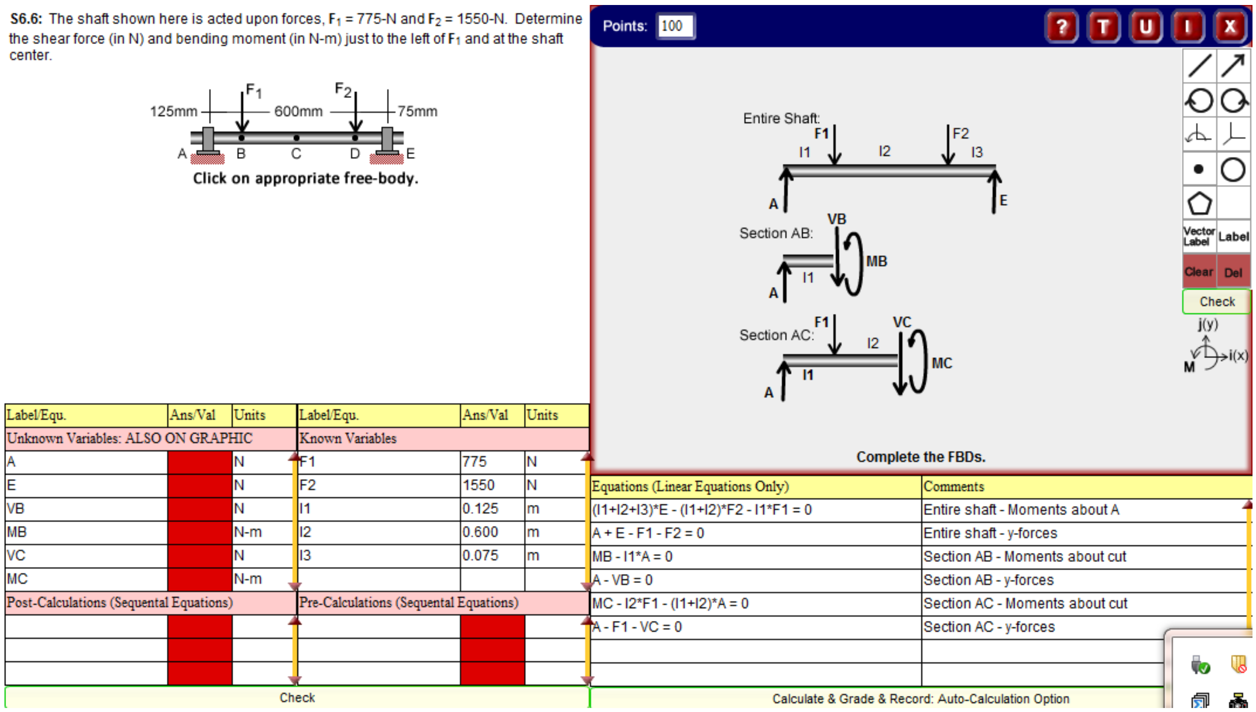

Figure 2: User screen prior to completing calculations

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 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 also sequentially evaluated. That is, any equation can use the known values or variables of any pre-calculation equations above it. 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 user interface and the post-calculation equations. The final user screen illustrating the result of these calculations 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. These equations are also sequential. A typical example of a post-calculation is an axial stress calculated from an unknown internal force (from the "Equations" section) and section area (from the "Pre-Calculation" section).

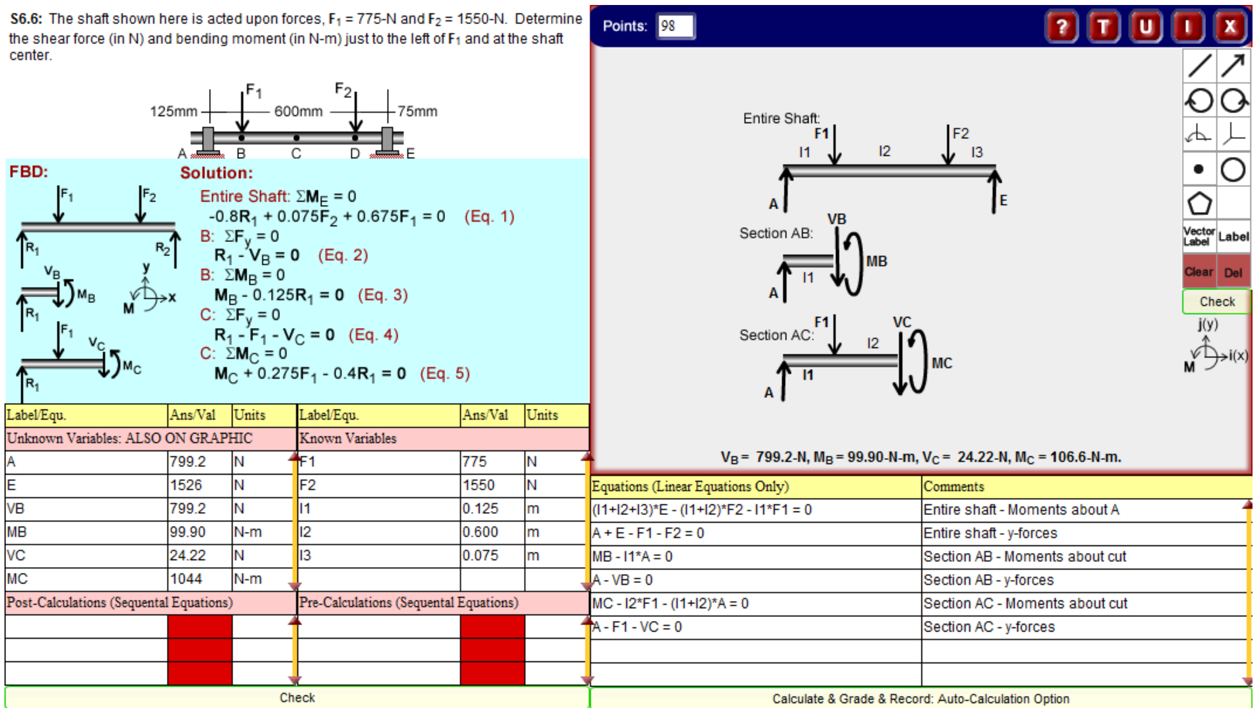

Figure 3: Final User Screen

The last section to be completed by the user 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- or 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 system of equation and post-calculation equations are then solved. Next, the values of the unknown variables and post-calculation variables are compared against the answers produced from a set of correct answer equations provided by the problem designer. If the problem statement includes random parameters, the problem designer must provide correct answer equations for the unknown and post-calculation variables that only include constants and the random variables. User answers are considered incorrect if they are not within +/- 1% (at the discretion of the designer) of the designer's answers. Incorrect user answers are highlighted and the user can proceed to edit any item on the screen and recalculate their answers. The user's opportunity to revise a solution based upon feedback is known to achieve deep, lasting learning (Suskie[19]).

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 can then be used to create a new M-MODEL problem or edit an existing problem.

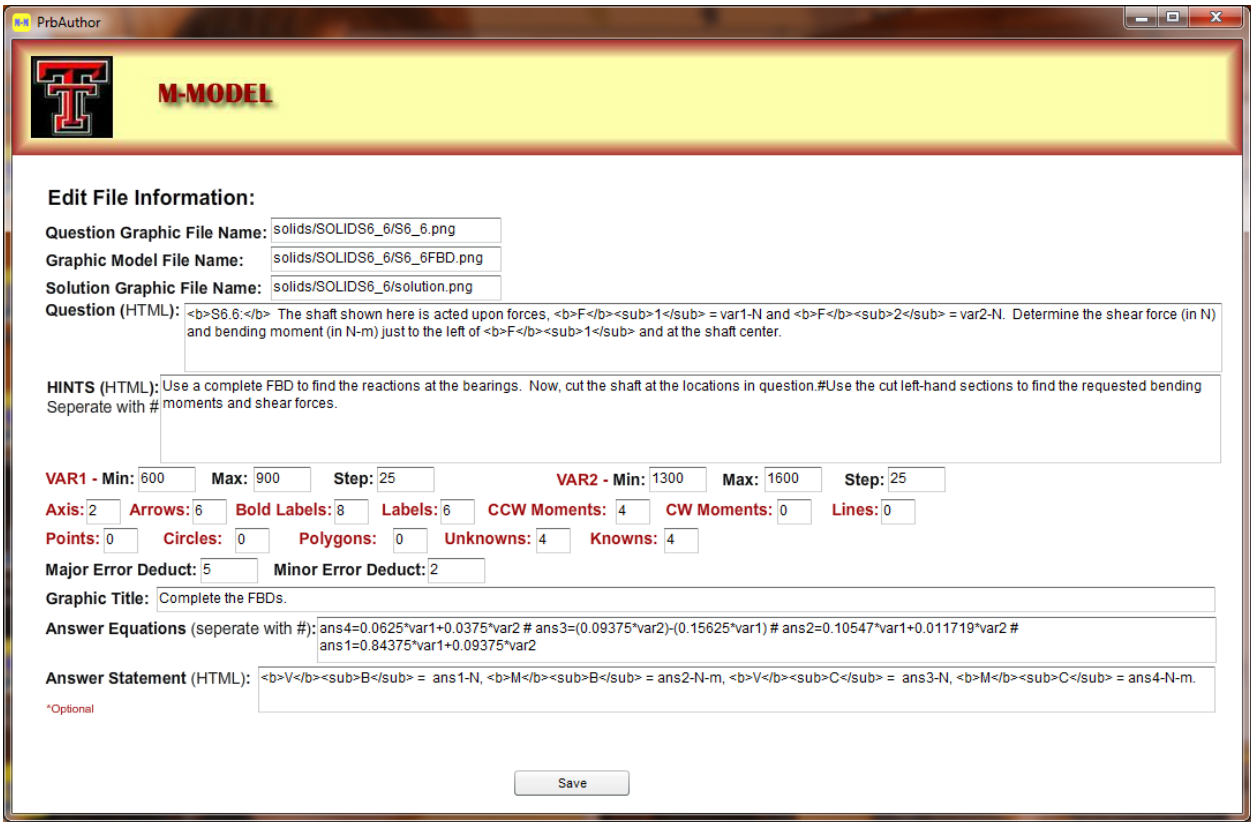

Figure 4: Problem Authors Form

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. Author hints or standard hints separated by the "#" character are entered in the Hints: field. 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-dimensional) 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. Point deductions for major and minor errors are entered into their respective fields. The title for the graphic construction 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 and ans2, using standard equation notation. These 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. These correct answers are denoted by their label. This form is saved as an xml file in the same directory and with the same file name as the problem statement graphic file.

M-MODEL Pedagogues

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 users must complete four of the six models (pre- and post-calculations are optional), they can be completed in any order. They can also be altered before final solution as one model provides further insight into another model. For example, users often add or remove variables as they are writing their equations or refining their graphic model. These cognitions 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[20]). Both are at the higher-order cognitions end of Bloom's taxonomy.

M-MODEL allows users 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 **A** and **E** as pre-calculation variables or as unknown variables. In the latter case, the user must include an additional equation in the equation section and the **A** and **E** labels in the graphics panel. Users may also elect to not use **A** at all, but rather to replace it with the appropriate moment equation. Other users may elect to use some or all numerical values in lieu of variable labels and values. All of these choices are correct as long as they are consistent and will produce correct answers. Users 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 through and detailed set of models, and often they need to refine or rebuild their models as their understanding of the problem deepens. This entails additional work on the part of the student which frequently meets with objection. Users 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 although the work of VanLehn[18] suggests that this may not be an issue.

Assessment

An experiment was conducted at the US Air Force Academy 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 N = 57, mean = 2.02 and SD =11.01 and for the untreated students they were N = 73, mean = -1.38 and SD = 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:

- It takes time to learn the interface
  - M-Model version 9 addressed these comments by making the interface more intuitive
- It takes more time to solve homework problems this way
  - Embedded elapsed time data were measured. A typical problem required 10-12 minutes to complete with a grade ranging from 86% to 95%.
- I got lost
  - Hints and tips have been added to address this issue
- M-Model requires too much detail
  - The author can only presume that students have been missing some of the important details required to understand a problem
- I learned more because of feedback and opportunity to immediately correct my mistakes
  - 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 9 has addressed the majority of the issues raised by the students.

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 pedagogue of current 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 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]. Several interface issues were raised by student users. These issues have been addressed in the current version 9 of M-MODEL. Interested readers may visit a demonstration version of M-MODEL at http://aln.coe.ttu.edu/anderson/premier/default.swf.

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