Re-Engineering Open-ended Problems & Computer Simulations For Effective Development of Student Design Skills

R. J. Eggert and S. A. Tennyson
Boise State University
Boise, Idaho 83725

ABSTRACT
Considering the broad philosophy of Design Across the Curriculum (DAC), a variety of strategies can be employed to integrate engineering design coursework during the four-year curriculum using just-in-time learning, an increasing breadth-then-depth approach. The sophomore and junior years, in particular, can be used to reinforce introductory design activities experienced as a freshman, and to develop enhanced design skills, readying students for senior design and eventual practice.

New multi-media courseware, such as Bedford & Fowler's ***Engineering Mechanics*** (1995) which incorporates Working Model© simulations, utilizes prepared learning modules to simulate the behavior or performance of bodies subjected to various forces and moments. While these simulations are "open-ended" they have little, if any, design content**.** Rather, what is needed, is an overall context, a firm foundation of how open-ended problems and simulations serve the whole design process.

This paper describes one dynamics example as prepared by Bedford & Fowler and a custom module that models a bungee jumper. Then, the educational aspects of these examples are discussed in the context of design content. A framework of guidelines is presented for educators, including the example bungee jumper problem reconstituted for enhanced design skill development.

1.0 INTRODUCTION

What is an open-ended problem? What is a design problem? Is there a difference? What role does simulation play in open-ended problem solving, or in the design process? How can engineering science problems be posed as design problems? In general, where and how should design fit into the four-year curriculum?

The engineering faculty at Boise State University considered these aspects and others during the spring of 1996, as we designed the 131-semester credit hour curriculum for the Mechanical Engineering Department recently chartered by the state of Idaho (1995).

While ABET specifies minimum criteria for four year engineering programs, the Mechanical Engineering faculty agreed to exceed these minimum requirements. Namely, we agreed to develop and deliver appropriate, high quality and comprehensive course work exceeding the minimum requirements for ABET accreditation, especially with regards to Design and how to integrate *design across the curriculum*. The essential aspect of DAC is that "…. Design cannot be taught in one course; it is an experience that must grow with the student's development" (ABET, 1996 a).

A draft policy on DAC was prepared and distributed to the faculty in August 1996. A revised draft, specific to the Mechanical Engineering program, was reviewed and adopted by the department in May 1997. In it, an underpinning design philosophy encourages design throughout the ME curriculum, involving a progressive breadth and depth strategy for appropriate design knowledge, methods, and skills, to be included in most of the required ME courses. The following design emphases were suggested to help faculty develop their curriculum: freshman year- design as a process; sophomore year - solving open-ended problems; junior year - component and system design; and senior year - capstone design project.

This paper primarily deals with using carefully constructed open-ended problems and simulations, which enhance design skills, leading to more effective DAC. The following sections discuss open-ended problems and simulations in engineering science analysis, the effective use of computer simulations, engineering design research at BSU, desirable design skills, and methods of posing engineering problems to enhance design skills. Design problem examples are also presented and discussed.

2.0 SOLVING OPEN-ENDED PROBLEMS

2.1 Open-ended Problems

Open-ended problems may be defined as those that have more than one answer, that the problems are defined in such a manner that they do not close-in on a particular or unique solution. Such problems typically pose non-specific situations, in an ill-defined fashion, requiring a variety of assumptions, which produce a multitude of feasible solutions.

In the process of solving an open-ended problem, the problem solver makes assumptions, explicitly filling in the blanks by assuming specific values for problem variables and parameters. Then, by substituting these values into a system of well-defined modeling equations, the problem solver analyzes whether a solution has been obtained. The modeling equations are usually derived from mathematics, science, engineering science, and economics.

For example, consider the following open-ended problem:

> **Determine the diameter and height of an upright, cylindrical container that could hold at least 100 cubic meters of water. Assume that strength and deflection issues can be ignored.**

The problem solver could choose to consider the minimum volume requirement of 100 m^3 and, for sure, the relation $V = \bullet\ D^2 H / 4$. The "solution" is represented by an infinite number of combinations of diameter and height that satisfy the volume requirement. This problem can be made more open-ended by relaxing the constraint that the shape must be cylindrical, thereby permitting spherical, box, and pyramidal shapes. As shown in this example, open-ended problems can also help to develop critical thinking and creativity.

2.2 Computer Analyses and Simulations

Once the modeling equations have been assembled, the functional performance of an object can be *analyzed* or predicted. *Analysis*, in particular, can be defined as the problem solving process of predicting an object's "function" once given the input "form" information. This is shown in Figure 1. Note that in addition to numerical analysis, other methods can be used to determine functional performance such as physical experiments or physical scale modeling and testing.

Computer hardware and software such as programmable calculators, custom computer programs, or spreadsheets are often utilized to assist in the required calculations for typical numerical analyses. Other software, such as Working Model©, also *animate* the predicted motion.

Figure 2 shows an example dynamics problem using Working Model© (Bedford & Fowler, 1995). As the RUN button is moused, the bar oscillates about the pivot joint. During the motion, three bar graphs track the kinetic and potential energy of the spring and bar as a function of bar position. Two slider controls can be manipulated to change the spring constant and bar mass, thereby changing the period of oscillation and the bar's range of motion. The user can click and drag the bar to various positions, also displaying corresponding changes in the velocity and position meters, and the energy charts, that is the five functional performance variables. The display response is instantaneous on a Pentium 166 MHz PC.

The benefits of computer simulations and animations are numerous:

- Automated computation. Computer simulations automate the model computations. In the example above, the five output variables were computed automatically, instantaneously. This is particularly important since simulations typically occur in a time domain. The state of the system, therefore, must be determined at each time step over the time span of the simulation.
- Behavior Animation. Graphical user interfaces animate corresponding changes in position, synchronized and scaled to the numerical analyses time steps.
- Quick Feedback. Quick feedback of analysis results cannot be overemphasized. Quick changes in energy and position, in the Bedford & Fowler example, clearly illustrate the engineering science concepts. Many "what-if" type questions can be quickly explored.
- Performance Envelope Exploration. Unexpected object or system behavior can surprise and educate users to phenomena that can and does occur in physical models. Users can explore the object's performance envelope, *before* a physical model is made.
- Focused Attention. The user's attention is focused when interacting with a computer simulation, such as manipulating the sliders, or inputting variable values. The user cannot be disengaged. The user is actively engaged and learning.
- Previously Prepared Modules. The Bedford & Fowler problems are pre-modeled, requiring only, to be "OPENED" and "RUN." Valuable student learning time is not wasted on the computer modeling learning curve. Similarly, correct models provide correct results.

However, computer simulations do have associated costs:

- Hardware & Software Costs. In addition to the hardware costs of a moderately capable PC, the user must buy and install the application software packages.
- Learning Curve. Applications require varying amounts of time and energy to become familiar with their basic operation. Then the problems have to be modeled and verified.

- Limited Modeling Features. Models are idealizations of the physical world. Assumptions used in the software may not be obvious to the user. Also, some engineering problems may not be adequately "solved" using computer simulation software, requiring physical experimentation instead.

2.3 Purposes of Design Related Simulation

Computer simulations, generated by software such as Working Model©, serve numerous purposes both directly within the design arena and outside this arena.

Outside the Design Arena:

- Simulate a completely defined physical system with the goal of reinforcing basic scientific principles, for instance, conservation of energy in a conservative system. This activity lies completely within the realm of pedagogy.
- For the same physical system simulate with the goal of learning how performance parameters behave in time. For instance, discover at what points in time that extremes of velocity, acceleration, and force occur. This endeavor can be poised in such a way as to be strictly pedagogical. On the other hand, placed in another context, understanding the behavior of performance parameters of a system can serve as an important "prelude" to design activities.
- Again for the same physical system, vary one design variable at a time in order to discover how the response of various performance parameters changes. As an example, for a system of masses connected by springs, vary a spring constant and study the change in response of the masses. This kind of endeavor can also serve as an important "prelude" to design activities.

Within the Design Arena (See Section 4.1 for more information):

- Employ a simulation package to verify an independent "analysis engine" developed for use in the evaluation phase of design.
- Employ a simulation package *as* the "analysis engine" for the evaluation phase of design.
- Use a simulation package to verify functional performance of a "design solution" over its range of different operating conditions

3.0 RECENT DEVELOPMENTS IN ENGINEERING DESIGN AT BSU

3.1 Design Related Grants

Through proposal efforts led by Professor Joseph Guarino, Chair of the Mechanical Engineering Department, Hewlett-Packard gave BSU a major grant in 1995 to develop and employ computer methods aimed at enhancing engineering education. The grant provided funds for Vectra personal computers and BSU provided a site license for Working Model© from Knowledge Revolution. Professor Guarino then developed custom Working Model modules (i.e. model files) that he used in both statics and dynamics courses.

The primary objective of the grant was to reinforce engineering science concepts by having students solve interesting simulation problems having many feasible solutions, aspects of creativity, and which could be verified by basic principles. An additional objective was to include design content.

Kathi Cahill, a master's degree candidate at that time in the Instruction & Performance Technology Department, joined Professor Guarino's research efforts in 1995. Ms. Cahill prepared assessment instruments to measure the influence of the new modules with regards to student learning and course satisfaction. Custom-designed assessment instruments were found to produce valuable information as to the effectiveness of adding a design component and may show the strengths and weaknesses of the course instruction (Cahill, Eisley, and Guarino, 1995).

Also, during the project, Professor Guarino developed an interesting hypothesis for the creation of learning modules, that the number of target concepts (i.e. engineering science concepts to be learned) should be equal to the number of changeable design elements (i.e. parts, or components in the mechanical system).

Professor Guarino prepared a follow-on proposal entitled “Design-Based Engineering Education on the Internet” which was subsequently funded by the Idaho State Board of Education in 1996, under the Technology Incentive Grant Program. This grant involves faculty from the University of Idaho, Idaho State University and Boise State University and use of the Internet. Working Model© modules will be developed and assigned in statics and dynamics courses and distributed on the Internet. Assessment instruments will be developed and administered in the 1997/98 academic year. Other research efforts are planned by the authors to specifically address design skill development across the curriculum.

3.2 Bungee Jumper Fun

Dr. Guarino developed the Bungee Jumper problem, shown in Figure 3, under the HP grant as an example of using simulation to reinforce underlying mechanics principles related to dynamics.

The Bungee Jumper problem is a classic open-ended problem. It has many acceptable solutions. Also, since the spring constant is *under the control* of the problem solver, it can be designated as a *design variable* or *design parameter*. The problem can be classified as a case of conventional parametric *design analysis* (Brinson, et. al., 1997) since an acceptable value of a design parameter is being sought.

In running this simulation for the first time it is immediately apparent that the bungee jumper collides with the ground for the default spring constant; a situation universally interpreted as being undesirable. By interactively adjusting this constant upward by trial and error, a value is reached at and above which the jumper no longer collides with the ground. Upon recognizing that the system is conservative it can be seen the conservation of energy principle dictates the system response entirely. Furthermore, the single relationship embodying this principle can be easily manipulated so that minimum ground clearance can be calculated for any chosen spring constant. The student can then verify their calculation by re-running the simulation.

This simulation serves well as an analysis instrument to discover the performance envelope of the system. The effects on the system performance parameters can be observed by varying the one design parameter. Students come to understand that minimum ground clearance is directly proportional to bungee-cord spring constant. The inclusion of an implied *design constraint*, collision with ground, as a natural driver to motivate student curiosity to explore system performance was truly ingenious! However, the problem as it stands contains only a paucity of design content.

Is the Bungee Jumper problem a "good" design problem? What constitutes a "good" design problem? What constitutes a "good" *design simulation* problem? Does the student develop any design skills in solving this problem? What specific design skills are being reinforced? Can the student learn more about design if the problem was slightly re-engineered?

4.0 LEARNING DESIGN SKILLS

4.1 What is Design Anyway?

Design can be defined *as a decision making process to determine the shape, configuration, and size of a product or process and the materials and manufacturing processes* used to make it. This can be summed up by the quote from Louis Henry Sullivan "Form ever follows function" (Sullivan, 1896). Design, therefore, is a process during which many decisions are made, often including the use of many different decision making methods or tools depending on the problem at hand. This is graphically shown in Figure 4. Notice how this differs from analysis as presented in Figure 1. In analysis we are given form and are required to predict function. In design, we start with desired function then determine what acceptable forms are satisfactory.

Another, widely published definition of design, was developed by the Accreditation Board for Engineering and Technology (ABET, 1996 b),

> "*Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective.*"

Design problems, therefore, can be described as *those that require decisions about form*s that satisfy function or "stated objective." Since many design problems have more than one solution, design problems are typically open-ended. Open-ended problems are not necessarily, however, design problems.

How can one determine if a problem has design content? To answer this question, let's examine some of the decision-making skills that are used in the design process. Five major aspects of the design process can be established: 1. formulation, 2. generation of alternatives, 3. evaluation of alternatives, 4. refinement and 5. documentation. Each of these categories encompasses a variety of decisions and decision-making skills, as shown in Figure 5. Davis et. al. (Davis, 1995) have defined 8 similar categories of design competency which parallel the five categories above. Note in particular that analysis is a sub-activity in the evaluation of a design. For example, analysis could predict the extent of an object's motion using laws of physics. Evaluation, on the other hand, asks whether or not the motion is acceptable, or if desirable, how "good?" Or in other words, analysis predicts how much or how feasible. Evaluation determines how good, or how optimal? Evaluation could be said to be the consideration of the customer, whereas analysis is the domain of Mother Nature.

The detailed listing of design skills, shown in Figure 5, hints at how we might begin measuring the breadth and depth of design "content." As a suggestion, one might measure design content by surveying the quantity and quality of decisions to be made in "solving" the design problem.

Simple yes/no or go/no-go decisions have a single decision, thereby earning perhaps a 1 or 2 quality rating index. Those comparing costs versus benefits have more quality however. These decisions consider aspects of more is better", "less is better" or "target value is better." Just establishing what "better" means, requires more design effort and therefore rates a higher quality index rating, perhaps 4 or 5 value. A design content index (DCI), therefore, could be formulated as the sum of the number of decisions weighted by their quality rating: $DCI = \bullet\ n_i Q_{Ri}$.

Consideration should also be given to the development of an objective measure of the effort required to complete a design problem, i.e. a solution effort index (SEI), which might quantify the approximate time requirements and other resources needed. As educators, we could use the SEI to determine appropriate design assignments. The authors are investigating these and other measures of design content and solution effort in their research. It is anticipated that these objective measures, which analyze design content, will be useful in synthesizing effective design assignments.

4.2 How to Re-Engineer Problems and Simulations

If we consider that the primary objective of engineering science is to create a bridge from the natural sciences and mathematics to the practice of engineering (ABET, 1996), how does design fit in? What educational objectives do we wish to achieve? How should we do it?

We are confident that students can develop a better and deeper understanding of design and learn desirable design skills if we re-engineer their assignments to include appropriate design content. While our work has not been fully developed yet, we do offer the following guideline: ***If a problem lacks design content, then add design content to require decision making.*** That is, if the stated problem has little design decision making, then restate the problem by infusing aspects of the five design process / skill categories from Figure 5.

For example, if a problem shows one configuration, require alternative configurations, thereby enhancing creativity. If a problem is clearly stated or defined, fuzz it up, requiring the student to sort out relevant information. If the problem ignores "how good" a candidate design is... require an evaluation criterion such as low cost, safety factor, low weight, or speed of performance. Pose two competitive criteria, forcing an evaluation or resolution of trading off one criterion for the other. Require sketches of alternative details, such as connections of members and a discussion of manufacturing tolerances. Instead of asking for an answer in units of pounds or feet, ask for a discussion of the values, using relevant terminology, graphics and mathematical symbols, thereby improving design communication skills.

As proposed, design content can be included in engineering problems and simulations. The re-engineering process may be difficult at times, however, when determining how much and what type of content to add. The inclusion of just one design decision may avalanche a twenty-minute homework problem into a two-week project. Would it make sense to develop some skills first and others later? Also, is it better to assign mini-projects during the semester rather than trying to include design content in most homework problems? While we do not have the answers to these questions, we offer the following suggestions:

1. explicitly identify the design skill or skills you wish to develop

2. determine whether the design skill is one of knowledge or proficiency
3. explicitly recommend a design method for a specific task
4. restrict the number of design variables (e.g. to less than three)
5. explicitly declare upper and or lower limits on design variables
6. explicitly state what considerations are to be examined or ignored
7. suggest a sequence of steps or a problem solving plan of attack
8. restrict the analysis to be done by a specific pre-modeled computer simulation, and
9. establish level of precision.

4.3 Bungee Jumper Problem: Re-Engineered for Design Content

In light of the discussion in the previous section let us reconsider the bungee-jumper problem, design-enriched with expanded decision making opportunities. For instance, just adding free-fall distance (rope length plus unstretched bungee length) as a design parameter along with some performance constraints can serve as a spring board to introduce students to a decision-based, guided-iteration design process. A reposing of the problem could proceed as follows:

Problem Statement (Customer Based)

A tower is available with a platform at 100 ft above the ground to convert into a bungee-jumping station at an amusement park. In order to draw customers this amusement must be perceived as thrilling and fun, but from the standpoint of liability - virtually fail-safe. Similar amusements have been highly successful in which customers experience a high free-fall velocity and high restoring force during deceleration, and see the ground come "close up" upon maximum excursion. This amusement will be limited just to adults. The bungee system will be non-adjustable, that is, rope length plus unstretched bungee length are to be fixed, as well as the bungee-cord spring constant. For preliminary design purposes, determine the "best values" for these parameters.

Resource Information Provided (hypothetical data only)

(i) Jumper weight will effect performance - 99% of adult population falls within weight extremes of 100 lb to 250 lb.
(ii) Upper limit for safe impulse (vertical mode) is considered to be 500 lb.-sec.
(iii) Upper range of safe deceleration (vertical mode) is from 3.0 g to 4.0 g.
(iv) Bungee/jumper harness to get no closer than 15 ft to ground per customer.

Here students begin the solution process by first converting problem statement and resource information into a problem formulation, also known as a design specification. The solution process presented from here on follows the methods given in Engineering Design and Design for Manufacturing by Dixon and Poli (Field Stone Publishers, 1995). The flow chart in Figure 6 illustrates this solution process.

Problem Formulation (Design Specification)

Set the Problem Definition Parameters (PDPs) to be,
(i) Mandate customer weight limits to be within 100 lb $< W <$ 250 lb.
(ii) Convert impulse (imp) into an equivalent velocity (V),

$$imp = (W/g)(V_{initial} - V_{final})$$

Since final velocity is zero, then $V_{initial}$ becomes 45 mph based on W = 250 lb; this is then maximum free-fall velocity (V_{max}).
(iii) Set upper limit of deceleration (G_{max}) to be no more than 4.0 g.
(iv) Set closest bungee/jumper harness clearance with ground (GC_{min}) at 15 ft.
(v) Set jump height (H_1) at 100 ft.
(vi) Take gravitational constant at g = 32.2 fps^2

Set product performance to be,
(1) Maximum peak velocity (V_f) for each jumper within specifications,
(2) Maximum deceleration (G) for each jumper within specifications,
(3) Minimum ground clearance (GC) for each jumper within specifications.

Specify Solution Evaluation Parameters (SEPs)
Solution Evaluation Parameters (SEPs) are the means by which the quality of a design solution is evaluated. They are assigned qualitative importance levels typically as: Very Important, Important, or Desirable. Note that since deceleration and ground clearance are dependent on jumper weight there need to be five SEPs,
(1) Maximum peak velocity (V_f) - Important
(2) Maximum deceleration at minimum weight (G_{Wmin}) - Very Important
(3) Maximum deceleration at maximum weight (G_{Wmax}) - Desirable
(4) Minimum ground clearance at minimum weight (GC_{Wmin}) - Desirable
(5) Minimum ground clearance at maximum weight (GC_{Wmax}) - Very Important.
[SEPs considered Very Important and Important are both safety and performance related, whereas those considered desirable are primarily performance related.]

Quantify Solution Evaluation Parameters (SEPs)
For each set of Design Parameters (DPs) selected, rope length plus unstretched bungee length (L_r+L_b) and bungee-cord spring constant (K_b), the SEPs can be determined analytically as follows:
(a) Peak velocity (V_f) is computed from constant acceleration kinematics,

$$V_f = [2\cdot g(L_r+L_b)]^{½}$$

b) Terminus height of free fall (H_2) is based on a geometric constraint,

$$H_2 = H_1-(L_r+L_b)$$

(c) Minimum ground clearance (GC_i) is computed from conservation of energy,

$$GC_i = \{K_b\cdot H_2-W_i -[(K_b\cdot H_2)^2-2\cdot K_b(½\cdot K_b\cdot H_2^2- W_i\cdot H_1)]^{½}\}/ K_b,\ i = 1,2$$

(d) Spring force (FSi) is based on the assumption of a linear spring,

$$FS_i = K_b(H_2 - GC_i)\ ,\ \ i = 1,2$$

(e) Deceleration (G_i) is taken as ratio of actual acceleration to gravitational constant, and is computed from Newton's third law,

$$G_i = (FS_i-W_i) / W_i,\ \ i = 1,2$$

When the counter i is set to 1, W_1 corresponds to minimum weight of 100 lb.
When the counter i is set to 2, W_2 corresponds to maximum weight of 250 lb.
The schematic in Figure 7 illustrates the parameters and variables defined in this section.

Qualify Solution Evaluation Parameters (SEPs)

The relationship between the calculated value of each SEP is then evaluated in terms of its quality. Usually the evaluation is expressed as Excellent, Good, Fair, Poor, or Unacceptable. A Satisfaction Graph is a convenient means to express this relationship.
Satisfaction Graphs devised for this problem are shown in Figure 8.

Use of a Dependency Relationship

In performing decision-based, guided-iteration design the DPs must be iteratively adjusted until a set of values is determined which is evaluated as representing the "best" design, assuming one can be found. In order to guide this process an arbitrary, empirical relationship has been devised which relates the change in each SEP to every DP,

$$SEP_n(old) / SEP_n(new) = [DP_m(old) / DP_m(new)]^{Dnm}$$

D_{nm} is an element of an n times m dependency matrix that relates the n^{th} SEP to the m^{th} DP. During the iteration process this relation updates information in two ways,

(1) If the m^{th} DP is changed from the *old* to the *new* iteration, D_{nm} can be updated for the *next* iteration.

(2) Based on current values of SEP_n, DP_m, and D_{nm}, an estimated value of DP_m can be predicted for the next iteration to satisfy a desired SEP_n value.

The dependency matrix can be displayed in a dependency table. Two tables for this problem are shown in Figure 9. Values in the "initial table" are guesses based on physical reasoning, whereas values in the "after 6th trial design table" are based on empirically generated updates throughout six trial design iterations.

Use of an Overall Evaluation Matrix

The last tool to employ in this process is the overall evaluation matrix - two samples from this problem are shown in Figures 10 and 11. After each trial design every SEP is located within this matrix based on its importance level and current satisfaction level. The matrix then gives rise to an overall evaluation of the trial design based on the conglomerate location of all the SEPs with respect to zones rated as excellent, good, fair, poor, or unacceptable. If the overall rating is concluded to be acceptable, then the current DPs represent the "best design", and the design process is complete. Alternatively, if the overall rating is judged to need improvement then at least one more trial design must be generated and evaluated. Here the overall evaluation matrix and dependency table provide invaluable information to guide the redesign. The overall evaluation matrix indicates which SEP to change to bring about the greatest improvement in the overall evaluation. Correspondingly, the dependency table indicates the DP for which the least change will bring about the greatest change in the SEP. Further, the target dependency element can be used to estimate what the new value for DP should be.

Solution for This Problem

A summary of the results for this problem is given in Figure 12. The dependency tables for the first trial design and after the sixth trial design are shown in Figure 9. The overall evaluation matrix for the first trail design, and sixth and seventh designs are shown in Figures 10 and 11. Guesses to start the first trial design evaluation were L_r+L_b = 50 ft and K_b = 40 lb/ft. Values for the "best design" after the seventh trial design were L_r+L_b = 36.5 ft and K_b = 18.1 lb/ft. Note although the values of all SEPs improved from the sixth to seventh trial design, the overall evaluation did not. Close observation reveals that further "fine tuning" of this design cannot improve the overall rating. Thus, the "best design" generated only has a "fair" rating. This does not reflect on the efforts of the designer nor the design methodology. Indeed, the combination of desired performance levels, imposed constraints, and physical laws dictated this result. The original model depicted in Figure 3 was modified to reflect the design parameters in this problem. Subsequent simulation verified functional performance of the "best design".

Other Suggestions for Adding Design Content

The bungee-jumper problem as reformulated is referred to as "preliminary design analysis" because the solution has no embodiment (form). Rope length plus unstretched bungee length (L_r+L_b) and bungee-cord spring constant (K_b) are not design variables, but functions of design variables. These variables are rope length, bungee-cord length, bungee-cord diameter, bungee elastic modulus, and number of bungee cords. A natural expansion of the problem would be a re-formulation in terms of these variables, and in addition include variables relating to the rope and bungee-cord load carrying capacities. A tower height greater than 100 ft could be included as a design variable, along with a cost penalty for greater height. Safe operation in spite of a rope failure or a bungee-cord failure during a jump would strengthen the problem, too. Thus, the problem expands to ten design variables:

(1) Rope length,
(2) Bungee-cord free length,
(3) Rope anchor height,
(4) Jump height,
(5) Number of bungee cords,
(6) Bungee-cord diameter,
(7) Bungee elastic modulus,
(8) Number of ropes,
(9) Rope proof load,
(10) Bungee-cord proof load.

The number of solution evaluation parameters expands to twelve:

(1) Peak free-fall velocity,
(2) Peak deceleration at maximum weight,
(3) Peak deceleration at minimum weight,
(4) Ground clearance at maximum weight,
(5) Ground clearance at minimum weight,
(6) Ground clearance, emergency,
(7) Impulse absorbed,
(8) Rope safety factor,
(9) Rope safety factor, emergency,
(10) Bungee safety factor,
(11) Bungee safety factor, emergency,

(12) System cost.

Commensurate with the expanded list of variables and parameters is the need for information about bungee-cord material, rope material, and tower cost factors in order to develop additional evaluation criteria. Efforts to solve this expanded version of the problem would certainly bring students further into the design arena. Nevertheless, any solution would still fall well short of full embodiment since *crucial* design details about how the various elements connect together, as well as harness design would be absent. Thus, this expansion of the problem is still predominantly "design analysis". If more design content were desired students could be asked to develop concept sketches for one or more of the design details.

5.0 CONCLUSIONS AND RECOMMENDATIONS

Simulations and open-ended problems, in general, reinforce topical material presented in lectures and reading. Most problems and simulations, currently published and available to course instructors, do not have design content. Design content, by definition, consists of decisions and decision making skills and methods. Engineering problems and simulations can be re-engineered to enhance student development of design method knowledge and design skill proficiency. Continuing research is needed to develop effective and efficient problem re-engineering techniques.

While ABET has mandated design across the curriculum, there is much debate and little evidence, as to how this should be accomplished. We contend that engineering problems, found throughout the curriculum, can be re-engineered by infusing design related information that requires design decision making. We suggest that the design process and related decision making skills can be used as a checklist of possible alternatives for that infusion. Also, it is recommended that appropriate design methods be introduced in the freshman and sophomore years. The junior and senior years could then be used to develop skills and design method proficiencies.

REFERENCES

Accreditation Board for Engineering & Technology, 1996 a, *1996/1997 Criteria for Accrediting Programs in Engineering in the United States*, section *IV.C.3.d.(3)(d)*.

Accreditation Board for Engineering & Technology, 1996 b, *1996/1997 Criteria for Accrediting Programs in Engineering in the United States*, section *IV.C.3.d.(3)(c)*.

Bedford, A., and Fowler, W., 1995, *Engineering Mechanics: Statics*, Addison-Wesley Publishing Company, Inc.

Brinson, L. C., Belytschko, T., Moran, and B., Black, T., 1997, "Design and Computational Methods in Basic Mechanics Courses," Journal *of Engineering Education*, Vol. 86, No.2, p.160, April.

Cahill, K, Eisley, M., and Guarino, J., 1995. "Summative Evaluation of Design Based Instruction for Engineering Students," Internal BSU project report.

Davis, Crain, Calkins, Gentili, Trevisan, 1995, "Competency-Based Engineering Design Projects," *Proceedings of the 1995 Annual Conference of the American Society of Engineering Education (ASEE)*, Washington, DC.

Dixon, J. R., and Poli, C., 1995, Engineering *Design and Design for Manufacturing*, chap. 17, FieldStone Publishers, Conway, MA.

Sullivan, Henry Louis, 1996"The Tall Office Building Artistically Considered," in *Lippincott's Magazine* (March)

Biographical Information

RUDY J. EGGERT is an Associate Professor in the Department of Mechanical Engineering at Boise State University. His research interests include Engineering Design, Design Theory and Methodology, Machine Design, Optimal Design, and Probabilistic Optimization.

STEPHEN A. TENNYSON is an Assistant Professor in the Department of Mechanical Engineering at Boise State University. His research interests include Engineering Design, Computer-Aided Design, Kinematics and Biomechanics.

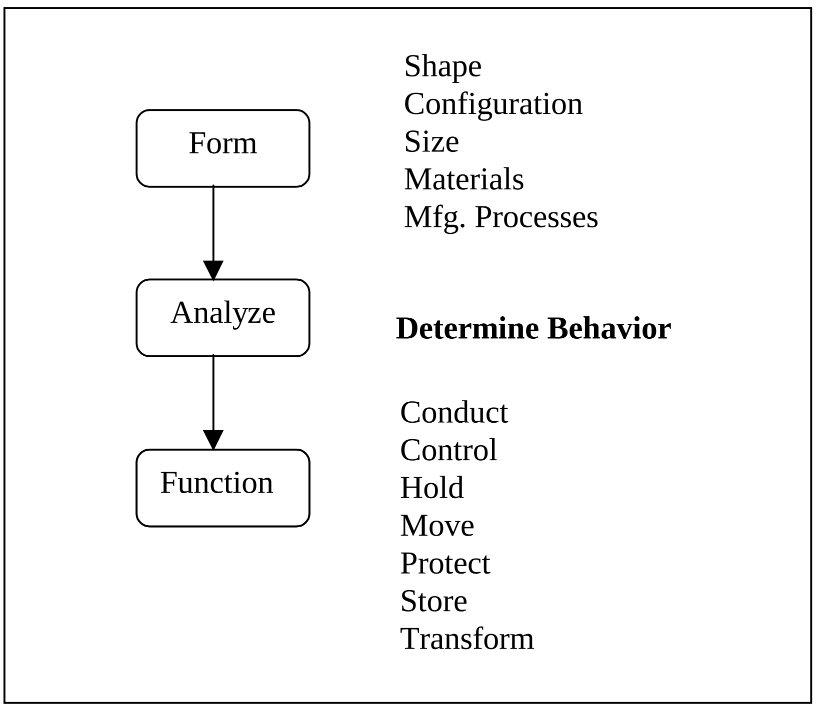


Figure 1. Analysis as function / behavior prediction.

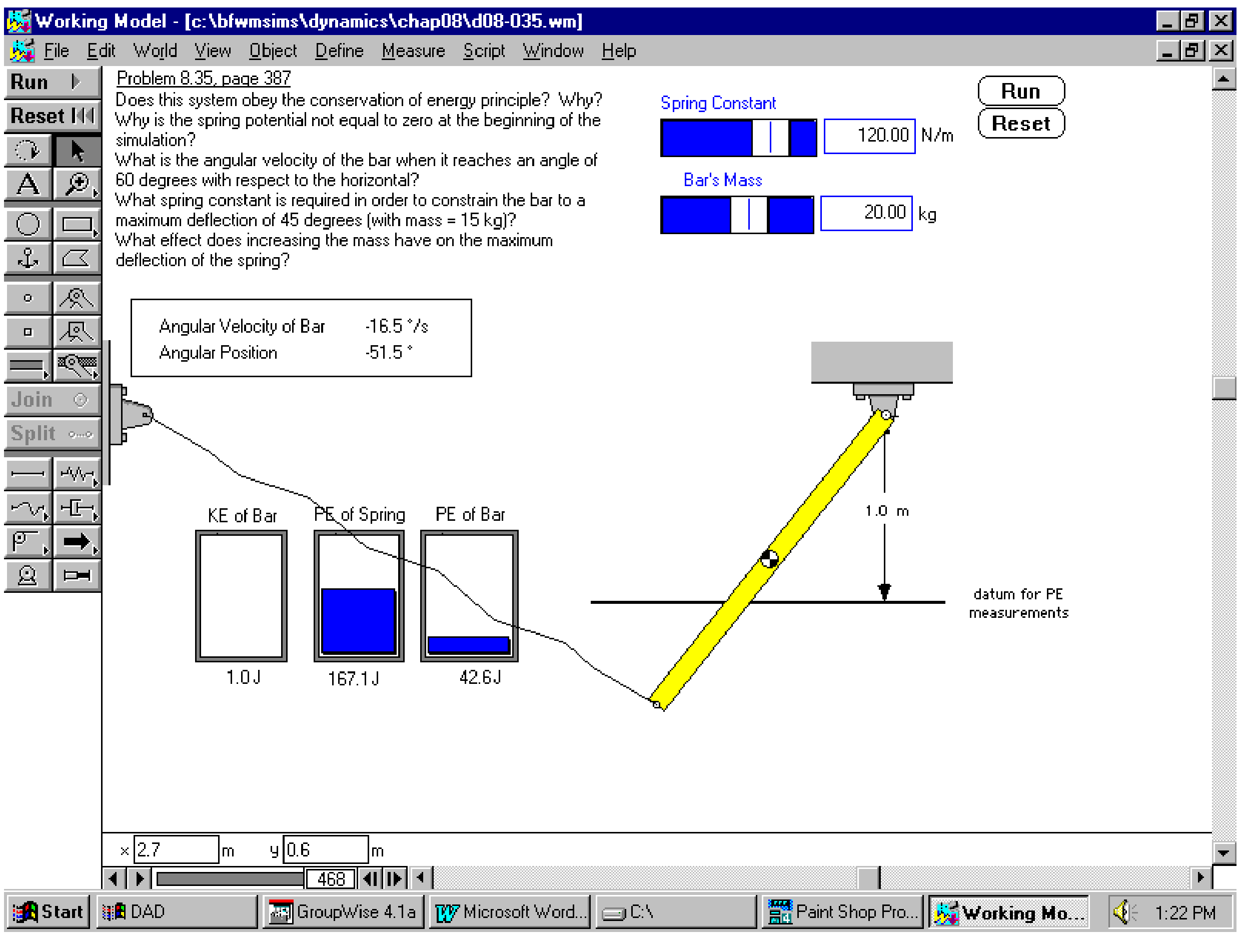


Figure 2. Open-ended dynamics problem (Bedford & Fowler, 1995).

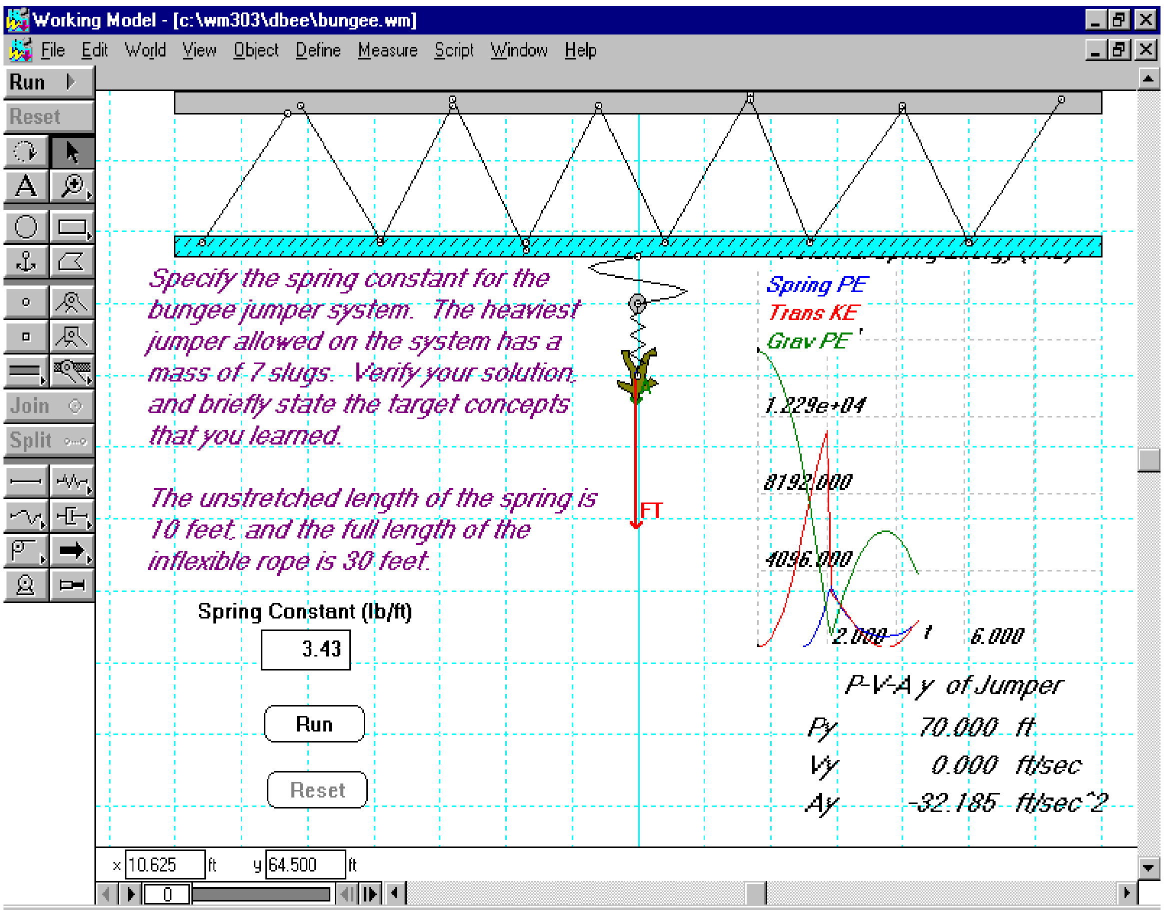


Figure 3. Bungee jumper problem.

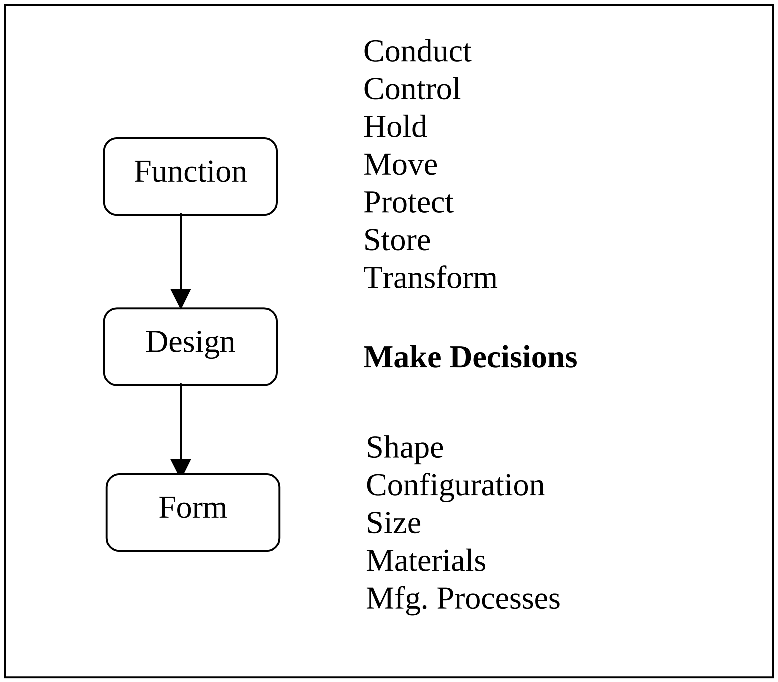


Figure 4. Design as decision making.

1. Formulation
   - Determining the “real” problem
   - Finding relevant information, exclude irrelevant info.
   - Specifying functional requirements / functional decomposition
   - Decomposing function(s) into sub-function(s)
   - Defining design evaluation criteria / QFD
   - Defining design variables
   - Determining constraints (e.g. physical, safety, economic etc)
   - Planning the solution strategy
   - Preparing an engineering design specification

2. Generation of Alternatives
   - Examining alternative, usable physical principles
   - Synthesizing alternative shapes, configurations, materials
   - Estimating/guessing starting values for design variables
   - Employing creative techniques such as brainstorming & synectics
   - Employing information resources (corp. Files, libraries, experts)

3. Evaluation
   - Modeling (mathematical, computer, experimental)
   - Using effective analysis methods / tools
   - Testing of product / prototype
   - Obtaining feasible solutions/ DFX
   - Evaluating analysis results
   - Selecting optimal solutions / Pugh, Dominic, Taguchi, NLP

4. Refinement
   - Detailing design, tolerancing, DFM
   - Automating iterative re-design / CAE, CAD

5. Communication
   - Writing - design spec.’s, technical reports, memos
   - Speaking - oral reports, conversations, meetings
   - Graphically - sketching, drawing, diagrams, charts
   - Employing effective use of engineering terminology

Figure 5. Design process categories and related decision making skills.

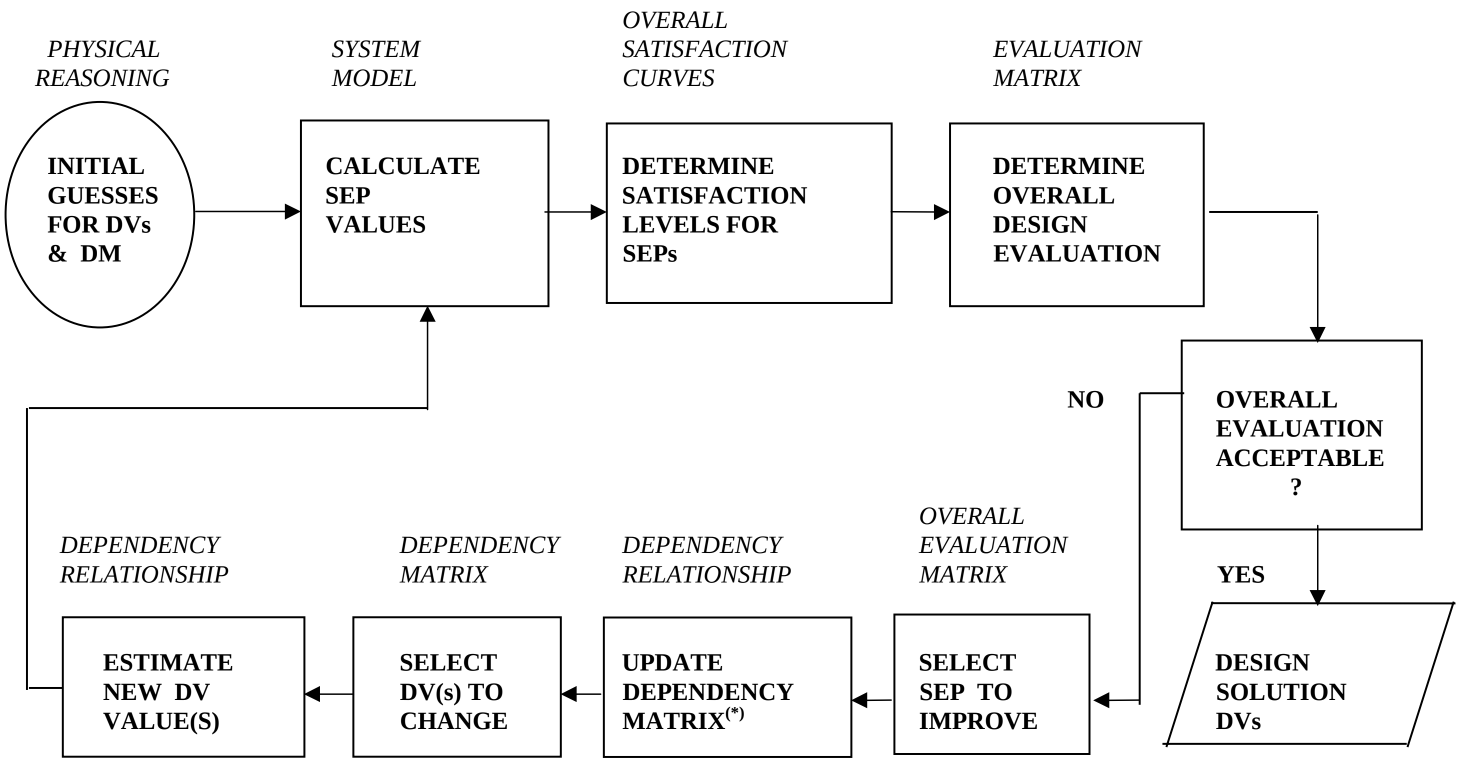


Figure 6. Flow chart for solving a decision-based, guided-iteration design problem , (*) After 2nd Trial.

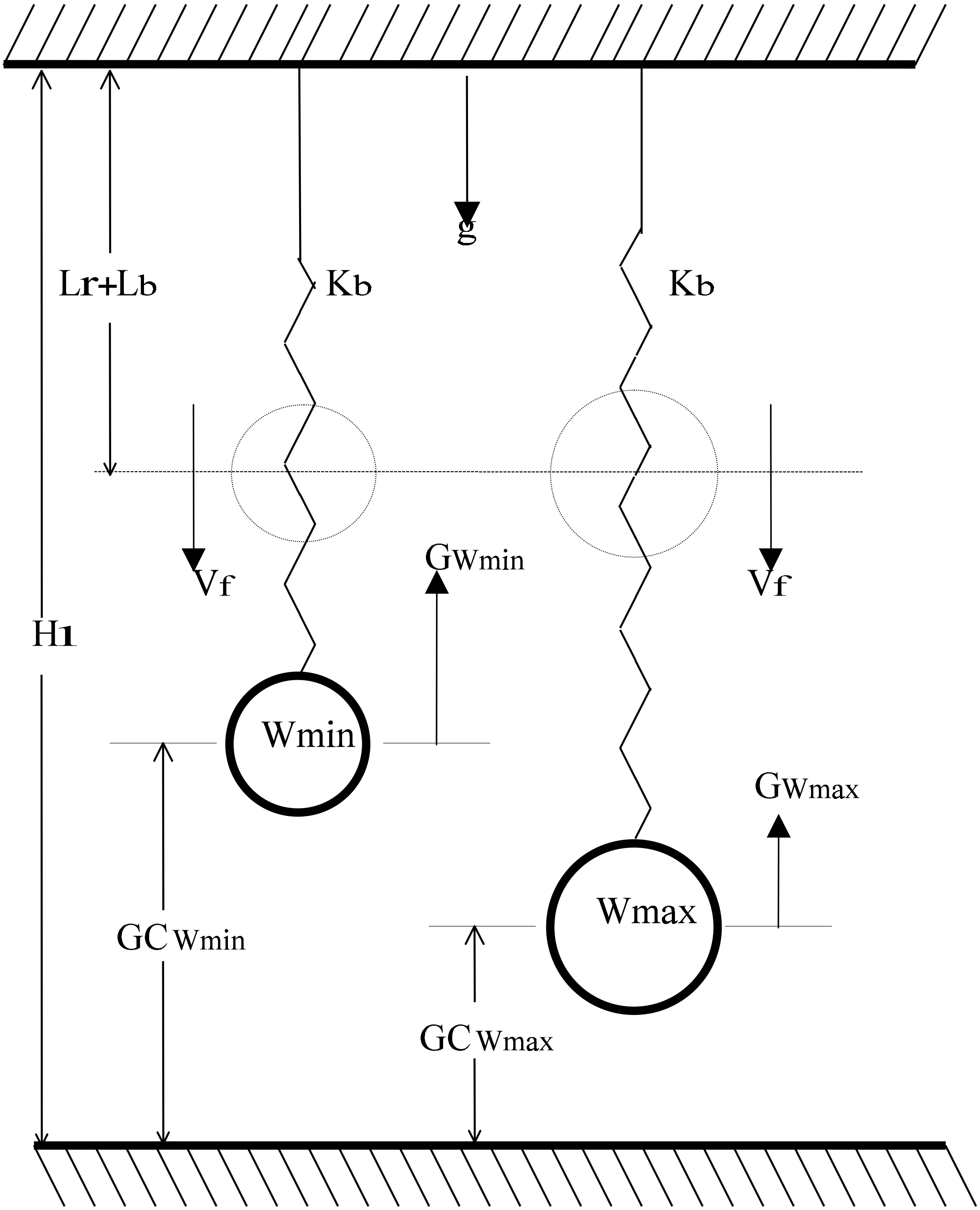
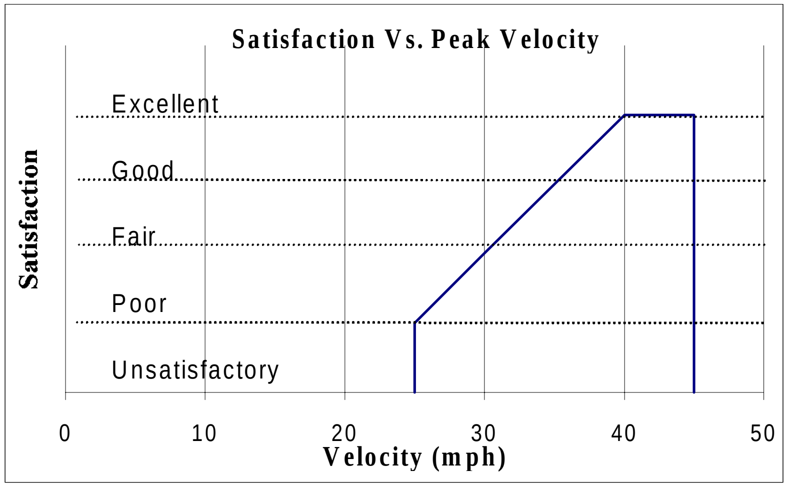
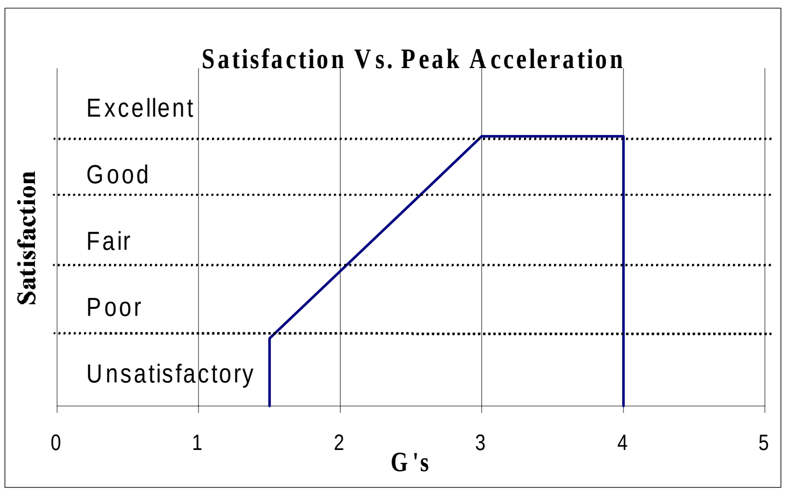


Figure 7. Schematic of two-varaible bungee problem.





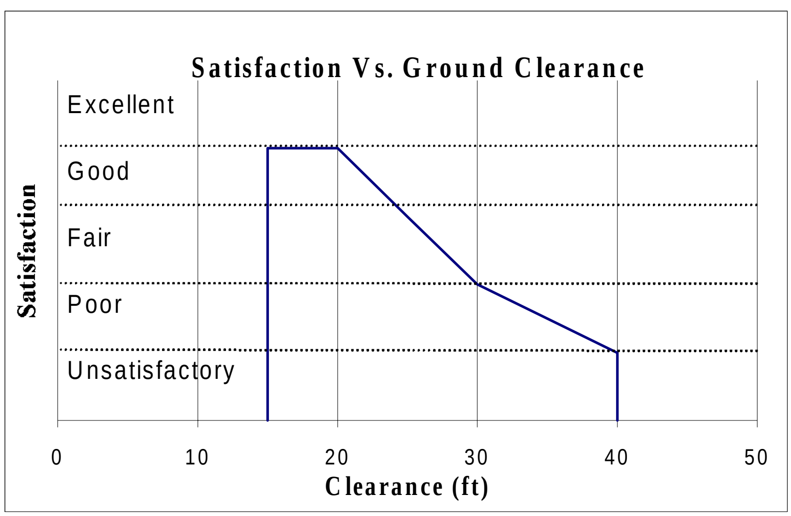


Figure 8. Bungee Problem - Solution Evaluation Parameter Satisfaction Curves

Initial Table	$L_{rt} + L_b$	K_b
V_f	D_{11} +0.50	D_{12} 0
G_{Wmin}	D_{21} +0.75	D_{22} +0.75
G_{Wmax}	D_{31} -0.75	D_{32} +0.75
GC_{Wmin}	D_{41} -0.75	D_{42} +0.75
GC_{Wmax}	D_{51} -0.75	D_{52} +0.75

After 6th Trial Design	$L_{rt} + L_b$	K_b
V_f	D_{11} +0.53	D_{12} 0
G_{Wmin}	D_{21} +0.36	D_{22} +0.47
G_{Wmax}	D_{31} +0.54	D_{32} +0.44
GC_{Wmin}	D_{41} -1.09	D_{42} +0.46
GC_{Wmax}	D_{51} -2.70	D_{52} +2.40

Figure 9. Two-variable bungee problem - dependency matrices.

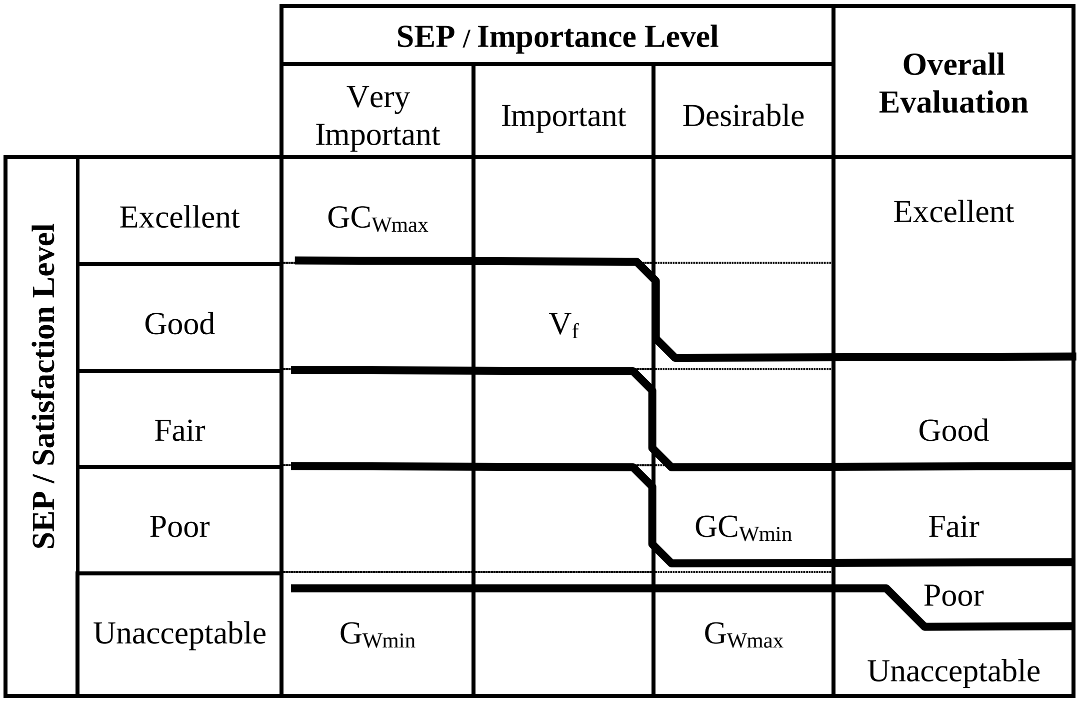


Figure 10. Two Variable Bungee Jumper Problem – 1st Trial

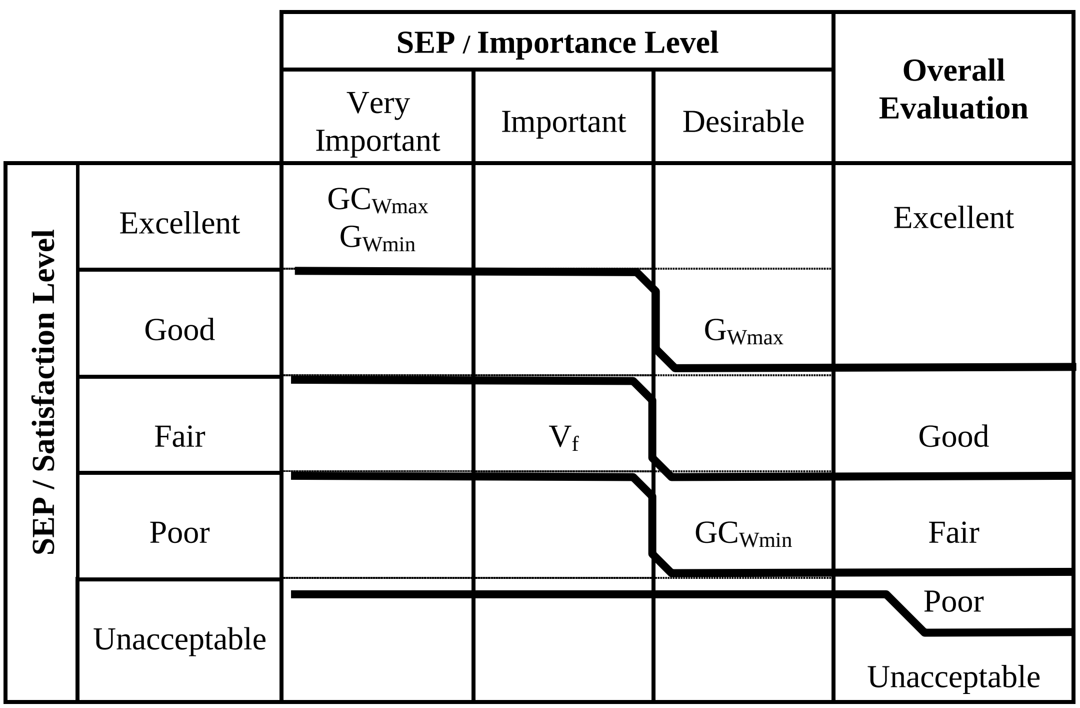


Figure 11. Two Variable Bungee Jumper Problem – 6th & 7th Trials

Trial Number	Design Variables		Evaluation Parameters					Overall Evaluation
	L_r+L_b (ft)	K_b (lb/ft)	V_f (mph)	G_{Wmin}	G_{Wmax}	GC_{Wmin}(ft)	GC_{Wmax}(ft)	
1	50.0	40.0	38.7(G)	6.4(U)	4.1(U)	31.5(P)	18.0(E)	U
2	41.0	40.0	35.0(G)	5.8(U)	3.8(E)	42.0(U)	29.3(F)	U
3	41.0	24.4	35.0(G)	4.6(U)	3.0(E)	36.1(P)	18.0(E)	U
4	41.0	18.1	35.0(G)	4.0(E)	2.6(G)	31.5(P)	8.8(U)	U
5	33.0	18.1	31.4(F)	3.6(E)	2.4(F)	41.6(U)	20.0(E)	U
6	35.6	18.1	32.7(F)	3.7(E)	2.5(G)	38.3(P)	16.3(E)	F
7	36.5	18.1	33.1(F)	3.8(E)	2.51(G)	37.1(P)	15.1(E)	F

Key: E - Excellent, G - Good, F -Fair, P - Poor, U – Unacceptable.

Figure 12. Two-variable bungee problem - summary of results.