

AC 2007-686: TOWER OF STRAWS: REACHING NEW HEIGHTS WITH ACTIVE LEARNING IN ENGINEERING DESIGN FOR THE FIRST-YEAR CURRICULUM

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Tower of Straws: Reaching New Heights with Active Learning in Engineering Design for the First-Year Curriculum

Abstract

Building a tower out of straws has been used as an activity for many years at all educational levels. In general terms, teams of students are provided with a fixed number of straws and fasteners (such as paper clips or straight pins) and are instructed to build a structure as tall as possible within a limited amount of time. Sometimes a constraint is added, usually that the tower must be able to bear a specified load or withstand other mechanical disturbances such as wind or vibration. Lesson plans for this activity are readily available on the Internet; the majority of them present the building of a tower of straws by a team of students as a methodology for developing cooperative learning skills. However, it is possible to modify this activity for use in first-year college engineering courses as an introduction to, or illustration of, the engineering design method. The scope of the problem is well-defined, allowing for the entire engineering design process to be accomplished within a short period of time. First, the problem is given to the class with appropriate constraints. Teams are formed to design and analyze possible solutions, which may include the development of drawings and/or prototypes. From the suggested solution alternatives, decision matrices are developed through classroom exercises for evaluating the success of the design against the set of original performance criteria determined by the students at the outset. Tasks are assigned amongst the team members, delegating roles for planning, design, and assembly of the structure. A testing protocol is developed and utilized following the building of the towers in class. Finally, reflection is used to help summarize the learning experiences in the areas of engineering design and teamwork, and how they can be applied in the future.

The purpose of this paper is to examine the methodologies successfully used at two institutions for implementing the Tower of Straws assignment and provides an assessment of its usefulness as an active learning exercise in introducing first-year engineering students to the engineering design process. The paper will describe two very different approaches to the same exercise, along with the assessment results from both Ohio Northern University (ONU) and Northeastern University (NU). The assessment tool maps responses to what the students perceive they learn about the design process steps and also assesses if the students learn engineering principles and teamwork the way the instructors intend for them. Suggestions for expanding on or modifying the activity for the purposes of engineering education and practical application will also be presented and all materials for implementing the Tower of Straws will be made available to educators in the appendices.

1. Background on the Tower of Straws Assignment

The Tower of Straws assignment has had a history of use in K-12 education. There are a variety of names offered to the exercise, as well as different sets of goals to be accomplished. Appendix A offers a sampling of 12 online resources related to this assignment. An analysis of data culled from these sites offers some insight as to the general characteristics of the typical Tower of Straws assignment. Obviously, all include straws as the primary construction material; however, the number of straws varies from a low of just 16 to a high of 200, with 50 being the most

common value. Additionally, while most implementations prohibited cutting straws, several allowed scissors as a tool. The materials used for connectors varied between paper clips, straight pins, and modeling clay. The basic constraints involved having a limited amount of time for construction utilizing only the provided materials. All examples indicated that this activity could be accomplished within a single class session. The predominant construction goal was to build the tallest tower; however, some versions of the assignment required being able to support a load: items specified included a tennis ball, a block of wood, and even two dictionaries. A couple of the assignments indicated as a criterion the ability to support the greatest amount of load. One assignment, which uses the Leaning Tower of Pisa as its inspiration, also included the ability for the tower to lean without falling as a criterion. The predominant teaching goals are teamwork and problem solving, with the physics behind such structures being implicitly involved in most cases and explicitly examined in a couple. Recommended group sizes ranged anywhere from two to five students, with ages ranging from elementary through high school.

Many of our students have had prior experience with a tower construction project and with construction projects in general during their K-12 experiences. A survey of the freshman engineering students at Ohio Northern University indicated that 24% had had some experience with a tower building assignment, and 50% indicated that they had had prior experience with construction-type assignments, primarily building either towers or bridges.

One item that the authors were unable to find during their background research was any assessment data pertaining to the effectiveness of any version of the Tower of Straws assignment. Consequently, one of the goals of this research is to gather this information from conducting two versions of this assignment at our respective institutions and to report upon the evaluation of the results in this paper.

2. Institutional Background

In order to understand the adaptations made by each institution to the Tower of Straws assignment, it is important to know something of the courses involved, including their goals and the particular engineering design methodology utilized.

2.1 Northeastern University. The College of Engineering at Northeastern University offers a first-year Engineering Design course during the entering semester. The course has similar goals and objectives to Engineering Design courses offered by other educational institutions, in that it promulgates teaching the principles of engineering through “hands-on” tasks for students in areas such as creativity stimulation, construction work, and associated reporting in relation to projects the students produce in teams. The philosophy of the Engineering Program is reflected in the students’ first course in Engineering Design: Promote and deliver practical, memorable, applied education with requirements for technical knowledge, opportunities for innovation, and the prospect for recognition.

At Northeastern University, the students’ introduction to the phases of the engineering design process is initially set out for them by use of the principles as espoused by Voland in his book “Engineering by Design”¹. The students are exposed to two substantial design projects and a variety of smaller assignments. The projects follow the stages of engineering design process and are aligned with Voland’s outline in the first chapter of his book. Specifically, Voland identifies

the following five primary tasks or phases and one contemplative stage of the engineering design process:

1. Needs assessment,
2. Problem formulation,
3. Abstraction and synthesis,
4. Analysis (of alternatives),
5. Implementation, and
6. Reflection and iteration.

The first design project, called the Minor Project, is typically a building project that exposes the students to the design process and gives them a chance to foster creativity. The second “Major” design project does not require the creation of a working prototype and therefore is more focused on assessing the student’s ability to analyze and apply all phases of the design process to a particular topic in greater detail and over a more extended time period than the first project.

2.2 Ohio Northern University. The College of Engineering at Ohio Northern University requires all freshmen in their first quarter to take Freshman Engineering 1, which introduces the students to the engineering profession and application of the engineering method. This includes identification and definition of problems, consideration of assumptions and constraints, generation of problem solutions through the application of standard engineering techniques, and communication of results through standard reporting formats. Part of the goals for this course is that students effectively work in teams to accomplish the tasks, use the engineering method to generate solutions to analysis and design problems, and develop technical documents typical of engineering practice. To this end, two books are used in this course: “Introduction to Engineering Design and Problem Solving,” by Eide *et. al.*,² provides the engineering component whereas Beer and McMurray’s “A Guide to Writing as an Engineer”³ provides the technical writing component. Students are presented with both independent and team-oriented assignments during the quarter, including a minimum of two “hands-on” engineering design problems assigned to teams of three to five students. Chapter 2 of the Eide book presents engineering design as a 10-step process:

1. Identification of a need,
2. Problem definition,
3. Search for information,
4. Constraints,
5. Design criteria,
6. Alternative solutions,
7. Analysis,
8. Decision,
9. Specification, and
10. Communication.

3. Tower of Straws Assignment Adaptations for Teaching Engineering Design

This section describes the approaches adopted by each of the participating universities for implementing the Tower of Straws activity. While there are many similarities, the differences

highlight opportunities to emphasize varying elements of engineering design. This section also presents the specific activities used at the two institutions during their respective fall terms in 2006 as arranged for this collaboration.

3.1 Northeastern University. At NU, the Tower of Straws activity is accomplished in one day as an in-class activity. It also serves as a team- and morale-building exercise. It is sometimes conducted right after Major Design project teams have been formed. Before the students are allowed to construct their towers, the instructor will facilitate a class discussion relating the exercise to real-world scenarios, focusing on limited resources, time constraints, and working as part of a team. Additional challenges are discussed and a variety of construction goals are created, some of which may be conflicting. Design criteria typically used as goals are:

- tallest tower – to the top or the flag,
- earthquake resistant – survives having the base shaken,
- hurricane resistant – survives a heavy breeze,
- aesthetically pleasing – subjectively determined by the class, professor breaks any tie,
- most creative – also subjectively determined by the class, professor breaks any tie,
- cost-effective – based on remaining materials following construction, and
- any others that the class selects.

In the NU Tower activity, the class also addresses working as a team, with guidelines that must be met to ensure that all members participate, as illustrated by the various groups shown in Figure 1. The building process provides many learning opportunities to reflect upon during that day and throughout the remainder of the semester. In this single-day format, the students learn that once started, there is not sufficient time to restart the task; thus good problem formulation, preparation, and planning are essential. They also learn that although height may be the “top” criteria, if it is not sturdy, one long set of straws will bend and fall over and most likely will not win the competition. This activity is intended to cover each of the design phases in an abbreviated manner: needs assessment, problem formulation (setting goals), synthesis, analysis, and implementation. Additionally, once the towers have been built, there is also reflection on how the task and their approach may have been revised. Reflection is crucial to review what they have learned about teamwork, constraints and engineering. Since this activity covers nearly all phases of the design process, it may be used at any point in the course.



Figure 1. NU Tower of Straws construction in progress, multiple teams and varying team sizes.

As seen in Appendix B, the instructor begins by dividing the class into groups of 4-5 students. One variation is to have the instructor set up group sizes with larger variation, from 2-7 students, and incorporate a discussion of ideal group sizes during reflection. Before starting, the goals are rank-ordered with weight values assigned collectively by the class. Each group is then given 25 straws of the nonflexible variety, a pile of paper clips and a small wad of modeling clay about 1” in diameter. The instructions are given to build the tower structure using the materials provided in a given amount of time. Examples of the students’ completed towers are seen in Figure 2.

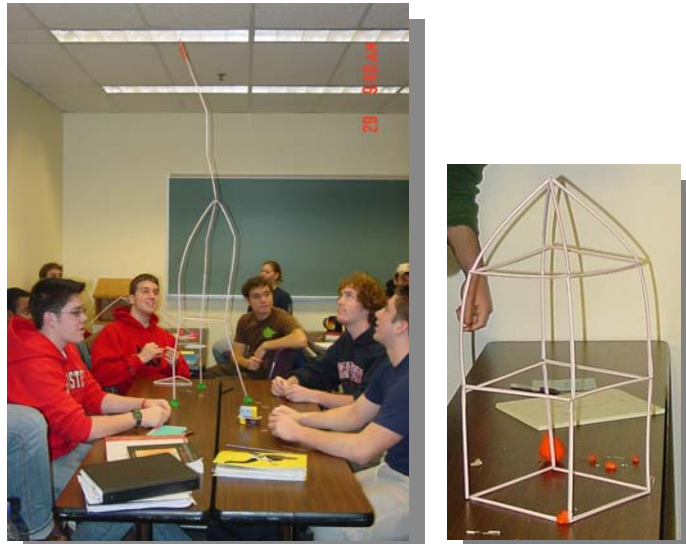


Figure 2. NU Tower of Straws, examples of completed structures.

The goal rankings are subsequently used in decision analysis following construction to determine which tower is “best”. An example of the design criteria used as goals are shown in Table 1. The time frame for goal ranking and construction is around 40 minutes, which leaves ample time for tower ratings and exercise reflection in NU’s 65-minute class period.

Table 1. Sample Decision Matrix from Northeastern University

DECISION MATRIX FOR		THE TOWER		Criteria Value 1 - 10 Rating Scale 1 - 5			
TEAM NAME (# MEMBERS) →		Eureka's Castle (4)	Building 19½ (6)	Team Emanon (3)	Tower of Power (5)	Team America (7)	Check This (2)
CRITERIA & VALUE							
HEIGHT	10	2 / 20	3 / 30	2 / 20	4 / 40	3 / 30	5 / 50
STURDY (shaking)	8	5 / 40	3 / 24	3 / 24	2 / 16	1 / 8	3 / 24
STABLE (wind/breeze)	7	4 / 28	2 / 14	2 / 14	3 / 21	5 / 35	2 / 14
AESTHETIC	5	1 / 5	2 / 10	3 / 15	5 / 25	2 / 10	1 / 5
CREATIVE	4	5 / 20	4 / 16	1 / 4	3 / 12	2 / 8	4 / 16
COST- EFFECTIVE	2	1 / 2	5 / 10	2 / 4	4 / 4	3 / 6	2 / 4
TOTAL FOR TEAM →		115	104	81	122	97	113

3.2 Ohio Northern University. At ONU, the Tower of Straws assignment is conducted twice, first in a single session early in the quarter for team building. Then the second version – the focus of this paper – is accomplished over a period of one to two weeks later in the term. Similar to NU, due to the nature of the ONU Freshman Engineering curriculum, three critical items had to be provided for this to be a successful team-oriented design exercise: constraints, criteria, and time. By stating a set of constraints, students are provided with a definitive goal that must be taken into account throughout all subsequent stages of the design process. A set of criteria must be developed for the purposes of evaluating competing designs. Some of the criteria flow naturally from the constraints; for example, having a tower capable of bearing a certain load as specified in the constraints can result in the establishment of a criterion that rewards designs that can bear loads greater than those specified. Additionally, the set of criteria should be generated to require students to consider design tradeoffs, such as the realization that having a greater load-bearing capability will result in a higher cost due to the larger amount of materials required, which would thereby lower the cost criterion score. The traditional Tower of Straws activity is typically introduced, designed, constructed, and finished within a single class period. This short amount of time is insufficient for students on a team to thoroughly perform many of the aspects of engineering design being emphasized in our curriculum, such as the examination of alternate solutions, performing an analysis to decide upon the best solution, and providing documentation of the specifications of their chosen design. This is the case in the first of the two times the Tower activity is done at ONU. However, in the second version, the students are given the assignment and are told that there will be an in-class competition on a particular date that is one or two weeks away. In this way, there is adequate time to have students work on the assignment both individually and as a team, and perform these additional desired tasks.

A copy of the Tower of Straws assignment provided to the students in the Freshman Engineering 1 course in Fall Quarter 2006 is provided in Appendix C. Each team of students was charged with the task of designing a tower of straws that had to satisfy the constraints of having a height of at least 7 inches tall and being able to support for a minimum of 30 seconds the weight of either a golf ball or a tennis ball that is located at least 7 inches above the base of the tower. The design was further constrained by the restrictions that the tower had to be built within a 10-minute time limit and could be constructed only from the parts supplied to each team at the time of the competition, as shown in Figure 3. Materials were 25 plastic straws, 50 #1 size paper clips, and a wad of modeling clay. The parts were assembled ahead of time by the instructors and placed in a one-gallon sized sealable plastic bag for each team. A paper plate was also included for use as a construction base if desired. Practice kits containing “gently used” parts were distributed to help facilitate design.



Figure 3. Parts used in the ONU Fall 2006 Tower of Straws assignment.

It was decided to present the students in each section with the evaluation criteria, and then let the students determine the relative weightings. These determinations were conducted in some sections as an in-class exercise whereas in other sections it was given as a homework assignment where the instructor would collect the data, tabulate the results, and present the results to the class at the next lecture. It was further determined that the best criteria to use would be those that are purely objective and easily measurable. Accordingly, the following criteria were selected:

- Constructability – measured by the amount of time required to assemble the design.
- Cost – measured by the total number of straws and paper clips used.
- Height – measured from the base to the top of the tower in inches.
- Strength – measured by the number of balls successfully supported above the constraint level by the tower.

Each student on a team had to independently create at least one preliminary design. The group then met to evaluate the preliminary designs based on the specified criteria and relative weightings through use of a decision matrix. An example of a preliminary design is provided in Figure 4. Following selection of the best design, each team developed a plan and instructions for the construction of the final design for their tower of straws. All of this material was incorporated into a written report to provide proper documentation of the team’s best design; this document was then submitted to the instructor following the completion of the assignment.

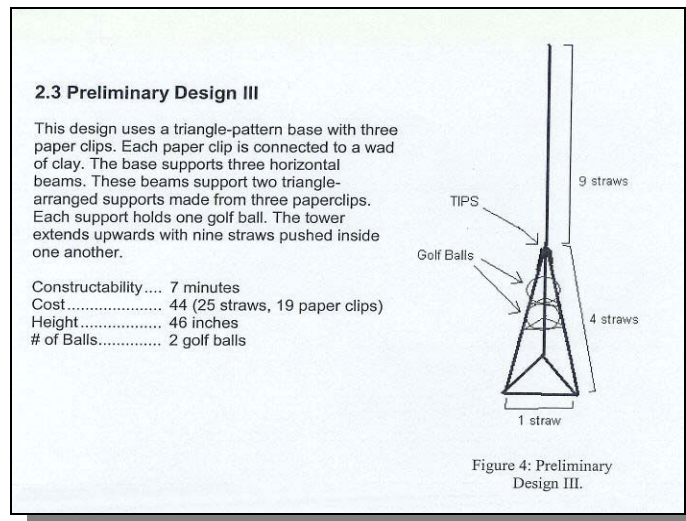


Figure 4. Example of a documented preliminary design.

One 50-minute class period was used for in-class construction and testing of the towers. The teams were assigned to tables, provided a set of parts, and allowed to begin construction. As constructability was one of the criteria, a stopwatch was used to keep accurate time; teams were required to visually indicate that they had completed their tower construction by holding up a sign with their team number, after which they could not touch their tower until it was time for load testing. The instructor enforced the time constraint by calling an end to construction once the 10-minute time limit had been reached. Each group then separately had their design evaluated against the constraints and scored against the criteria as the remainder of the class observed.

The testing protocol was as follows: When it was their turn for evaluation, each team first had the height of their tower measured, as shown in Figure 5. Once this was completed, they had to place their load onto their tower, an example of which is shown in Figure 6. A sufficient number of golf and tennis balls were made available by the instructor for testing individual designs. However, teams did have the option of “pre-loading” their designs; in those situations, the teams were required to supply their own loads of golf or tennis balls.

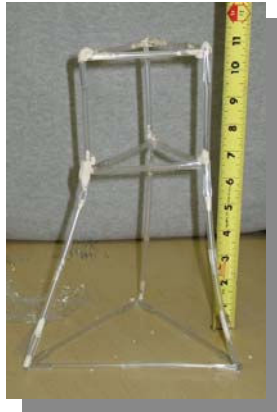


Figure 5. Measuring tower height



Figure 6. Loading the tower of straws.

Once the load was placed, a stopwatch was used to officially determine that the structure met the constraint of successfully bearing the load for at least 30 seconds. The final measurement to be made was cost. Following the completion of load testing, all teams disassembled their towers and placed their components into groups of five for ease of counting. The total number of straws and paper clips used was then recorded. During the activity, an Excel spreadsheet implementing a decision matrix was projected onto a display screen; as measurements were made, the data was entered in real-time, thereby showing up-to-date standings for each team. Once all teams were evaluated, the Excel spreadsheet displayed the results of the competition, including the rank order of finish. An example spreadsheet showing results from one section is provided in Table 2.

Table 2. Sample Decision Matrix from ONU Tower of Straws assignment

GE 104 Fall 2006 Tower of Straws Competition

Group	Group Members	Constructability, min.	Height, in.	# Balls	Cost	SCORE	PLACE
1	Danielle, Jenna, JC, John	10	13	2	57	24.7	6
2	Blair, Lauren, Lee, Sarah	8.53	12	2	51	38.3	4
3	Brad, Lucas, Joshua, Jameson	7	31.5	1	22	66.9	2
4	Michael, Nick K., Nathan, Max	10	11	2	43	28.2	5
5	Frank, Benjamin, Bobby, Jeff	8.63	40	3	35	81.1	1
6	Drew, Robert, Nick S., Nick T.	8.7	40.5	2	43	65.4	3
7	Phil, Jonathan, David, Bryan	10	7.5	0	34	3.4	7
Weights		25%	30%	25%	20%		
Max value		10			75		
Min value			7	1			

4. Assessment and Evaluation

Assessment is a vital element in engineering education to evaluate effectiveness and to be both responsive and receptive to areas of potential improvement. Accordingly, a common survey was developed at both institutions to be administered following the completion of the tower assignment. The survey evaluation tool was divided into three sections, all of which required the participants to reflect on the tower-building activity. Although, as noted earlier, this activity has historically been used as a team-building experience, the survey questions focused primarily on the learning points and how they may resonate with the students in the context of engineering design. Section I concentrated on the steps of the engineering design process; Section II included two open-ended questions about physical laws and scientific principles and polled the students' about similar past experiences; Section III inquired about other concepts not covered in the formal engineering design sequence. Please refer to Appendix D to review the evaluation questionnaire.

Section I of the questionnaire listed Voland's engineering design phases since ONU's 10-step design could be folded into the Voland model. The students were asked to place a check in the box next to each phase if they felt it was represented in the tower-building activity. If so, then they were to specify how strongly they felt it was illustrated such that 1 indicated 'barely shows that step' and 10 indicated 'very strongly illustrates the step'. Also, in the space below each listed step, they were to relate, in their own words, *how* the activity illustrated the design process with examples from their tower experience. Since this was not intended to determine whether the students remembered the specific steps of the engineering design process, each design phase was listed in the most familiar terms. This allowed the authors to ascertain not only whether the students could map the tower experience to the established steps of design process – and to what degree – but to describe the mechanism by which the phase was incorporated.

Section II of the assessment tool shifted the format and presented two brief-response open-ended questions which carried no singular correct answers. The first question was: "What engineering, physics, or scientific principles were demonstrated in the tower-building experience?" This inquiry was intended to associate the theoretical notion of design to the tangible necessity of possessing and actually applying technical knowledge. While some of the tower-building process is necessarily trial-and-error, the young engineers are reminded by this question that there are sound principles upon which much of engineering rests. The second question in Section II simply served to identify whether the students had experienced a similar activity in the past. This allowed the authors (a) to determine to what degree this was a duplicate experience, and (b) to review the examples that were provided for common elements.

Survey Section III addressed ancillary factors, additional points to assess, and other lessons learned relating to real-world applications and experiences. These concepts went beyond the design process to consider the other "lessons" one hopes to convey and competencies to be imparted in the 'introduction to engineering' educational mission. The quantitative elements in Sections I and III were then compiled and averaged for each university and evaluated separately in light of the differences in the administration and format of the assignment. The written responses from Sections I and II underwent a standard multi-pass content analysis for common terms and themes. Results are presented in the next section.

5. Results and Discussion

The following sections review both the quantitative and qualitative responses to the survey instrument distributed following the tower construction experience. Similarities and differences in outcomes between the participating universities are described and discussed below.

5.1 Quantitative Results. The NU and ONU survey ratings from Sections I & III were compared and contrasted to search for common themes and differences in the students' responses as to the illustrative and educational value of each principle put forth. The analyses have three elements:

- the *rankings* from highest to lowest in illustrative value,
- the *statistical differences* between the two universities' results, and
- the *level of variability* found in each of the relevant elements.

The common elements and differences provide insight as to the best implementation style of the tower activity according to the objectives and progress of the course. The analyses have been conducted bearing in mind the administration format for each of the participating universities: NU implemented this as an in-class construction challenge while ONU organized the activity as a homework design challenge to then be constructed in class. Also, the ONU teams had the additional stipulations of a preliminary design and the requirement to support the weight of a golf or tennis ball.

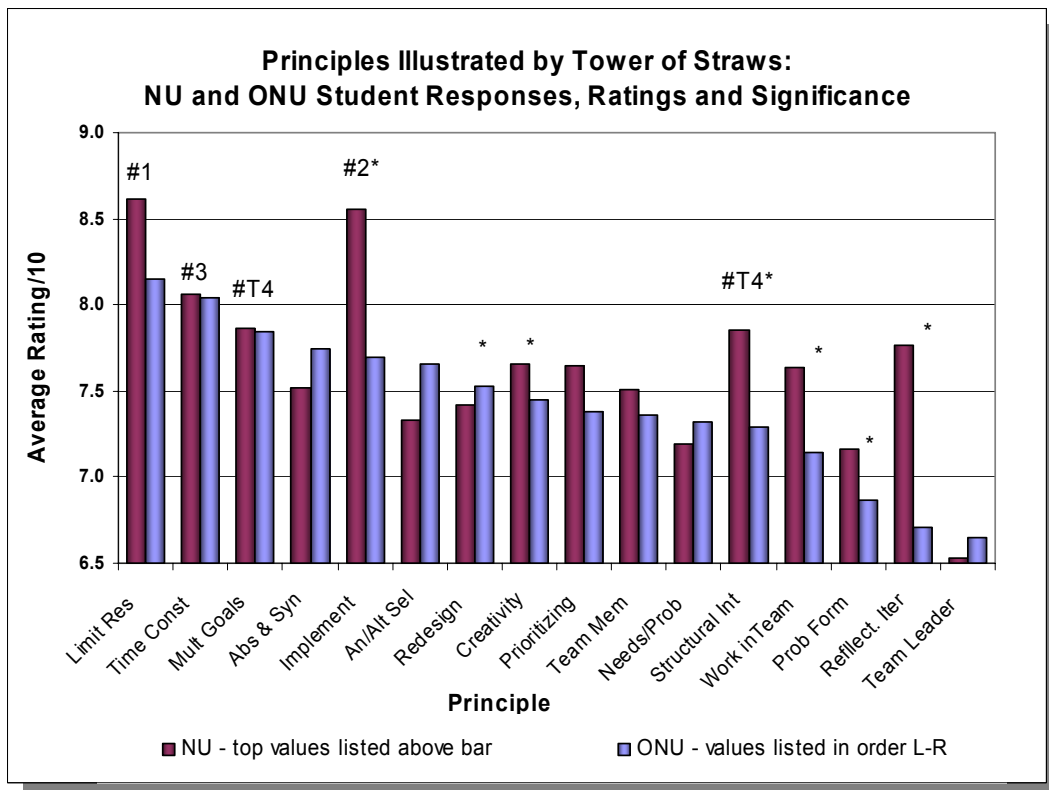


Figure 7. Rankings of principles for each University, T4 = tied for 4th in rankings. Significant differences between universities are denoted by * above each principle.

Figure 7 above presents the rankings of each of the principles listed in Sections I and III on the assessment survey. It is organized with NU on the left of each data pair and ONU on the right.

ONU rating results are set out ordinally; that is, the rankings are listed in descending order from left to right on the graph. NU data is plotted alongside the corresponding principle, in the leftmost column of the pair, as shown in the legend.

Regardless of the administration format, both populations of students determined *working with limited resources* to be the most highly illustrated principle in this activity (ranked 1 & 1, NU & ONU, respectively). Also common in the top four were *working within time constraints* (2 & 3), and *considering multiple goals simultaneously* (3 & T4). It is interesting to note that none of these top picks are explicitly from the list of formal design process steps presented to the NU students, yet their selections strongly correlate with those made by the ONU students, whose design process explicitly refers to constraints and criteria. Given the distinction in the two design process models, the NU instructors can use this opportunity to observe with the students that constraints and criteria also fit into the engineering design process as a subset of Problem Formulation.

The highest design process step rated for NU was *implementation* (ranked 2), while the highest-ranked design step for ONU was *abstraction and synthesis* (ranked 4). This is not surprising given the NU requirement to build the “product” in one sitting, while the ONU cohort had the time – and the requirement – to generate solution alternatives before construction occurred. The NU focus on the product delivery and the ONU concentration on design options allowed for excellent teaching points in each circumstance.

Also some notable similarities with the two populations were the lower rankings of *working as a team leader* (16 & 16) and *problem definition/problem formulation* (14 & 15) of the 16 presented principles. The *team leader question* functions as a strong validity check by design and is expected to be low in nearly all cases, as there was little opportunity for all participants to be a team leader in the time frames allotted. Furthermore, the problem definition had already been provided in each case, so these results are not surprising. However, concerning collaboration in general, *working as a team member* did not score highly across the board ranking (11 & 10), nor did *working in a team* (9 & 13). This suggests that given an activity that has been traditionally used for team development, engineering educators can in fact parlay the experience into a multifaceted design lesson.

Significant differences were found when comparing the universities’ ranking outcomes for certain principles. Independent t tests were performed at $\alpha = 0.05$ for each of the 16 principles. As seen by the asterisks (*) in Figure 7, a significant difference is shown for *implementation* (2 & 5), where $p < 0.001$. Also noteworthy is the difference shown for the *reflection and iteration* stage of design (5 & 15), where $p < 0.002$. These sets of differences may again be attributed to the administration element of the activity; under the in-class time constraints with very little planning opportunity, the NU group was given to reflecting on what they would have altered if they had more time and better prospects for planning. Since at NU reflection is explicitly defined and practiced as a critical part of the design process, this may in fact contribute to the large differences seen in the *reflection and iteration* rankings.

Another statistical difference worth noting is the *principle of structures and structural integrity* (T4 & 12). The NU teams were primarily concerned about building the highest tower in a limited amount of time. A few fell over before the decision matrix was completed causing a focus on the (lack of) structural integrity of the towers. Again, ONU teams could plan and practice to ensure

they met all requirements. Excellent lessons on technical knowledge and the value of planning result from both of the approaches under analysis.

In terms of variability, an interesting commonality between the two schools was the statistical variance of certain responses. For both NU and ONU programs, the largest standard deviations were found in *necessity of redesign* (1 & 2 in standard deviation) and in *reflection/iteration* (2 & 1 in standard deviation). The high variability indicates that individual students have varying opinions on the degree to which each of these principles is effectively illustrated in the tower activity. This suggests that there is no general consensus in either program in these two areas.

5.2 Qualitative Results. In Section II the first open-ended question inquired about the engineering, physics, and scientific principles that were demonstrated in the tower activity. Responses were well aligned with the technical knowledge required to undertake a construction project on any scale: structural design and integrity, gravity, stability, torque, forces, statics, teamwork, balancing competing criteria/trade-offs, budgeting materials, and the value of planning ahead. Most students readily recognized how essential these factors are to engineering success in general. These responses served as excellent discussion points in terms of further take-away value from the activity. There was also mention of concern by the students for those who left this response blank.

The second question concerning having done or seen a similar activity before yielded a variety of responses which included: paper towers, toothpick/stick bridge, balsa bridge, balsa tower, Knex® and Legos®, paper bridge, bridge with straws & tape, straw/paper clip tower that must hold weight/tennis ball, spaghetti bridge, card structure to hold cinder block, popsicle sticks and glue to hold weight, tower of newspaper, spaghetti and gumdrops, toothpicks and marshmallows, and newspaper cantilever to hold weight. The objective and value in learning of these activities is (1) determining the common elements of these activities, namely that they rely on ordinary, inexpensive familiar materials used in new ways and (2) identifying whether they have the potential to teach in engineering design like the Tower of Straws.

Finally, in terms of collecting supplementary feedback, a couple of exam questions were posed at NU which provided an excellent opportunity for further discussion on the learning value of the tower-building experience. The students were asked: *Name 2 objectives [your professor] may have had in mind by having you participate in the Tower-Building challenge. In other words, what were some of the embedded lessons in this activity?* Among the responses that were already seen in the survey, a particular concept emerged: “The effect of team size” was a recurring response as teams ranged from two to seven people in some cases. A quote by another student was very telling, and summed up similar responses that were prevalent across the sections:

“We automatically applied the engineering design process without even having to think about it.”

This is very encouraging as it reflects one of the fundamental competencies to be attained in the engineering design course: the ability to naturally, readily, and effectively apply what has been learned.

The students were also asked: *Describe one way in which the Tower-Building challenge was **not** a typical engineering design project.* The core of common results was interesting with students providing the responses related to the following:

- It is not a real-world need or actual set of beneficiaries.
- Background research has not been done.
- There was very little planning or opportunity to plan.
- An extremely limited time frame is given.
- The decision matrix is done after the project/design [has been implemented].

The third and fifth comments above on the time limit and decision matrix are indicative of how NU has implemented the Tower-Building challenge. All of these student-generated thoughts are mechanisms by which to emphasize the value of the engineering design process through the vehicle of tower-building experiences. As noted below, a follow-up discussion at ONU raised the same three issues seen in the first, second and fourth statements above, showing that factors that are conspicuous in their absence generate learning opportunities as well.

6. Unscripted Lessons

Among the outcomes of the research into the use of this assignment were the authors' encounters with "unscripted lessons;" those being the opportunities to create teaching moments out of unanticipated events. While there are always opportunities for such lessons whenever an instructor is in the classroom, this particular assignment sufficiently engaged the students such that there were a greater number of "unscripted lessons" than one would normally expect. These are discussed below.

6.1 Northeastern University. At NU and in general, students have often tested the interpretation of the constraints, raising issues about any perceived ambiguities in the instructions. One example is whether the tower must be freestanding or whether it may be attached to the ceiling or other supports. This is an opportunity to discuss 'client requirements' and the necessity for stating and clarifying design specifications at the outset of a task or project.

Concern about unequal team size has been expressed in the past, which also leads to a valuable discussion on how to best utilize personnel resources. Another outcome is a useful dialog on the 'ideal' team size for particular goals and projects according to the characteristics of each.

Due to the subjective factors designed into this activity at NU, another embedded lesson focuses on productive competition and the consequences of design choices. As the decision matrix is being scored to identify the "best" tower according to the initial criteria, the students soon discover for themselves that the decisions of the client (instructor) are, in effect, final and not necessarily negotiable. This goes back to raising their awareness to the merits of clarifying design goals and iterating, and recognizing the value of prototyping in a real-world circumstance in order to receive feedback on the proposed solution prior to implementing the final design.

Given the limited time frame from commission to completion, a new emphasis can be given to the value of planning and even to the notion of drawing, sketching and prototyping. This provides an opportunity to discuss the importance of generating and testing alternative solutions and evaluating multiple options before implementation. By design, the time limit does not allow these steps to be fully realized, contributing to the lessons learned.

6.2 Ohio Northern University. The Tower of Straws assignment was actually used twice during the quarter; what has been documented here was its second use. A very simple version asking groups of students to construct the tallest tower within a limited amount of time was used as an icebreaker exercise on the first day of class. Before the second version of the assignment was distributed, students in one of the sections were asked to reflect on the initial activity. Among the comments made during this discussion was that it did not constitute an actual engineering design problem because there were neither constraints nor realistic criteria. An impromptu discussion followed about the design and functionality of buildings, and the nature of the constraints and criteria therein.

From a historical perspective, it is interesting to note that three of the seven groups in the aforementioned section adopted the use of spires to achieve greater height in their design, although this was not explicitly mentioned in the class discussion. The adoption of spires in skyscraper design during the late 1920s and early 1930s played a pivotal role in acquiring “world’s tallest building” status. In the most notorious example, in 1929 the architect William Van Alen designed a 185-foot spire for the Chrysler Building that was secretly delivered to the site and raised to the top in only 90 minutes. This pushed the overall height of the Chrysler Building to 1,046 feet, surpassing both the just-finished 40 Wall Street building in New York City and the Eiffel Tower.⁴ A review of data from two sections showed that, out of 15 groups, six used a spire to achieve greater height; an example of such a tower is shown in Figures 8a and 8b. The average height of those towers with spires was 36.3 inches, as opposed to only 9.7 inches for those without spires. Consequently, this height advantage as evaluated by the criteria allowed these “tall” designs to rank higher than the spireless designs, even though some of the spireless designs were more functional in terms of greater demonstrated load capacity.

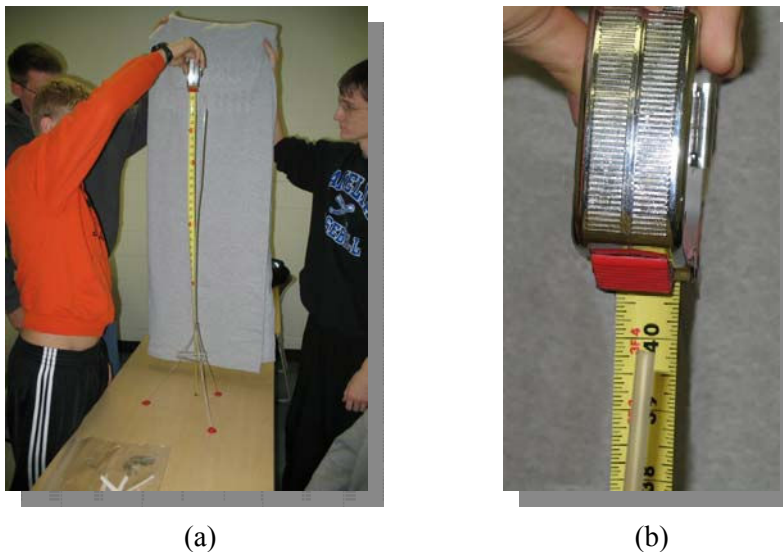


Figure 8. (a) Use of spire in Tower of Straws design. (b) Close-up of height measurement

7. Conclusions and Suggestions

This paper has examined the methodologies successfully used at two institutions for implementing the Tower of Straws activity and has provided an assessment of its usefulness as an active learning exercise in introducing first-year engineering students to the engineering design process. Observations from a student survey indicate that students from both universities rate many design elements similarly following this experience, with the fundamental differences explained by the administrative characteristics of the activity. In addition to the assessment outcomes presented here, the success of the Tower of Straws assignment has been quantified in a study of learning potential versus student perception of engagement conducted at NU for engineering design class activities⁵. Students reported a high level of engagement (4.2/5) and that they learned a relatively high amount (3.8/5) from “team-building” activities, which primarily represented the Tower of Straws experience in the majority of the sections polled.

To create a greater tie-in to real-world design, the Tower of Straws activity can be posed in the form of developing an inexpensive, hands-on model of the design of a water tower, in which the number of balls supported is indicative of the amount of water capacity and the height of the base of the lowest ball is indicative of the amount of water pressure. An area worthy of further investigation would be to hold an additional round of tower building, which would allow students to reflect upon and either refine or revise their original designs based on the feedback obtained and experiences gathered during the first round of tower building.

As shown in this paper, one can make this a lesson focusing on the design process completed in one class period or less, or an assignment covering all facets of the design process with more time for additional exploration worked on for a period of a week or more. With considered guidance from the instructor, the engineering design process can easily be illustrated in either format of the activity. The strengths of the Tower of Straws experience is that it is easily adapted to (a) serve as an introduction to engineering design early in the term, (b) highlight certain stages of the design process (c) fit the learning objectives of a particular lesson, (d) function to reinforce the established design steps later in the term, and (e) capture elements that are neither phase-related nor tangible yet are essential to design and engineering success.

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Appendix A. Online Resources for Traditional Tower of Straws Activity

Tower of Straws Site, Description of Activity, and URL	Team Size	Grade Level	Number of Straws	Number and Type of Fasteners	Tools
Georgia Applied Technology Education Association – "Straw Tower" Draw design of, then build, tower capable of supporting a tennis ball for 30 seconds. http://www.gitea.org/GITEA%20Problem%20Solving%20Cookbooks/Cookbook%201.pdf	3	?	100	Many pins	none
Maine State Curriculum Guide – "Space Structures" Design and build in 30 minutes freestanding tower that supports a tennis ball at its pinnacle for 60 seconds. http://www.usm.maine.edu/~zanerj/CurGuide/spacetruc.html	3	9 – 12	200	100 pins	scissors
Columbia Education Center – "Teamwork Towers" Work in a cooperative group to create a freestanding tower in 10 minutes. www.col-ed.org/cur/misc/misc14.txt	3-5	6 – 8	50	75 pins	none
Exploring Minds - "Tallest Tower of Straws" Plan in 15 minutes, and then build in 30 minutes, the tallest tower that supports the weight of two dictionaries. http://www.teteschercheuses.ca/e/students_secondary/creative_genius_program/pdf/short_challenges_04.pdf	2	6 – 12	30 + 20 coffee stirrers	20 paper clips	tape
Washtenaw Elementary Science Olympiad – "Straw Tower" Build the strongest straw tower at least 12" tall, scored as a function of both height and greatest mass supported. www.aaps.k12.mi.us/wesowizards_home/wesowizards.events/straw_tower	2	1 – 5	50	20 pins	scissors
Austin Peay State University Science ExpOlympics – "Plastic Straw Tower" Construct in 35 minutes a tower at least 15 cm high capable of supporting the greatest hanging load. www.apsu.edu/brennanc/ExpOlympics/Descriptions/straw_tower.htm	3	9 – 12	16	40 paper clips	scissors
Science and Mathematics Initiative for Learning Enhancement – "Building a Straw Power Tower" Build tower at least 58 cm tall, test, then augment observed weaknesses to support the most pennies in a bucket. www.iit.edu/~smile/chbi9919.htm	2-5	2 – 8	50	120 paper clips	scissors
Future Scientists and Engineers of America – "Straw Tower" Build tower to a specified height, width, depth, and tolerance capable of bearing the most weight. http://www.fsea.org/pdf/TW1%20Straw%20Tower.pdf	2	4 – 9	50	Many paper clips	tape
University of Wisconsin–Parkside – "Soda Straw Tower Contest" Create the tallest tower with the least amount of straws as part of an engineering design competition. http://oldweb.uwp.edu/academic/engineering/SodaStraw/	?	?	?	?	?
TeacherTECH – "The Leaning Tower of Straws Challenge" Construct a tower with at least 15 straws as high as possible that can successfully lean without collapsing. http://teachertech.rice.edu/Participants/pschweig/towerchallenge.html	?	9 – 12	100	Modeling clay	none
Georgia's Technology Education – "The Straw Tower" Design and build a tower as tall as possible that can support the weight of a tennis ball for 30 seconds. http://www.gitea.org/GITEA%20Problem%20Solving%20Cookbooks/Cookbook%201.pdf	3	?	100	Many pins	none
IST Solutions Exchange – "Team Building: Straw Tower" Build the tallest structure possible with 20 minutes of planning and 90 seconds of construction. http://solutions.ist.psu.edu/exchange/support/overview/courses/resources/straw_tower.pdf	?	?	25	none	none

Appendix B. Fall 2006 Northeastern University Tower of Straws Activity

GEU 110 – Fall 2006

Engineering Design Activity: Instructor Background Information

THE TOWER

Preparation:

- Divide class into teams of 3-6 people, a total of 6-7 teams works best
- Bring Sharpies® or markers to write on the flags, if you use them
- Allow all of 65-minute class period for the activity
- Prepare kits of materials as listed below
- Have a method for keeping time

Materials:

- Optional: A “flag” – piece of paper approximately 4” x 5 ½” to write team name
- 25 straws that are approximately 8 ¼ “ in length, contained with a rubber band
- 1 box, approximately 100 #1 size paper clips (but can obtain more if desired)
- 1 lump of clay, approximately 1½” x 1½” x 1½” cube
- No other material may be used

Time Frame:

- 0-5 minutes: post groups and have students sit together as they arrive
- 5-10 minutes: discuss decision matrices and generate criteria list and values
- ~5 minutes: distribute materials and give instructions for the Tower Activity
- ~25 minutes to build with 5-minute and 1-minute warnings, plus countdown
- ~10 minutes to test, evaluate and rate towers on the prespecified criteria
- ~10 minutes discussion, reflection, lessons learned and/or questionnaire
- ~5 minutes clean-up

Instructions:

In the time allotted, your team is to design and build a “Tower of Straws” that:

- Is as high as possible or attempts to meet other criteria to earn points
- Optional: Holds the flag at the highest point you can attach it
- Only uses the materials provided (teams may request more paper clips)
- Is free-standing, i.e., does not attach to the ceiling or any other structures
- Is completed with all members participating together as a team

When the allotted construction time has elapsed and the criteria rating begins:

- Vote for or rate each tower on how it meets each initial criterion on a 1-5 scale
- No touching, supporting, or further constructing your tower
- No sabotage to any other towers; no arguing, appealing, etc. ☺

Debriefing:

- Administer the Questionnaire and/or
- Discuss lessons learned/observations, student-driven as much as possible

Appendix C. Fall 2006 Ohio Northern University Tower of Straws Assignment

GE 104 – Freshman Engineering 1 – Fall 2006 Engineering Design Assignment: Tower of Straws

Your team is to design a "Tower of Straws" that satisfies the following constraints:

1. The height of the constructed tower must be at least 7" high.
2. The tower must be able to support for 30 seconds the weight of at least one tennis ball or one golf ball that is located at least 7" off the ground.
3. The tower is constructed using only the parts supplied to you:
 - 25 straws that are approximately 3.9" in length,
 - approximately 50 #1 size paper clips, and
 - a wad of modeling clay.
4. The tower must be assembled within 10 minutes.

In class on Monday, 23 October 2006, you will construct your design in class, after which each design will be evaluated to determine which team has the best design. In order to make this determination, we must establish both the evaluation criteria and the testing protocol to be used.

The following four criteria will be used for the evaluation of your design:

- Constructability – measured by the amount of time required to assemble the design.
- Cost – measured by the number of components (straws and paper clips) used.
- Height – measured in terms of the height of the structure in inches.
- Number of balls supported at a height of 7" or greater by the tower.

The respective weights for these criteria will be determined in class. The Design Points method will be used when the designs are evaluated. The testing protocol will be discussed in class.

Your team is to perform the following tasks:

1. Develop a minimum of one preliminary design per team member.
2. Evaluate your designs with a decision matrix utilizing the Design Points method to determine which preliminary design is the best.
3. Develop plans and instructions for the construction of your team's best design; please refer to Beer chapter 5, pp. 110-114, on how to write instructions.
4. A report containing your preliminary designs, your decision matrix, plans, and instructions for the construction of your selected design is to be turned in on the day of the event. Please refer to Beer chapters 5 and 6 for appropriate reporting format.

Appendix D. Common Survey Instrument for the Tower of Straws

Freshman Engineering 1
Fall 2006

College of Engineering

Tower of Straws Evaluation

1. For the steps of the Engineering Design Process listed below, place a check in the box if you feel that step is illustrated in the activity. Then on a scale of 1 to 10, indicate how strongly you feel it is illustrated where 1 indicates 'barely shows that step' and 10 indicates 'very strongly illustrates the step'. Also, in the section below each step, tell us in *How* it illustrates the design process with examples from your experience.

	Barely shows	>>>>>>>>	>>	>>>>>>>>	>>>>>>>>	>>	>>>>>>>>	Very Strongly Illustrates		
<input type="checkbox"/> Needs Assessment/Problem Statement: <i>How?</i>	1	2	3	4	5	6	7	8	9	10
<input type="checkbox"/> Problem Formulation/Problem Definition: <i>How?</i>	1	2	3	4	5	6	7	8	9	10
<input type="checkbox"/> Abstraction & Synthesis/Generation of Alternatives: <i>How?</i>	1	2	3	4	5	6	7	8	9	10
<input type="checkbox"/> Analysis/Alternative Selection: <i>How?</i>	1	2	3	4	5	6	7	8	9	10
<input type="checkbox"/> Implementation: <i>How?</i>	1	2	3	4	5	6	7	8	9	10
<input type="checkbox"/> Reflection/Iteration: <i>How?</i>	1	2	3	4	5	6	7	8	9	10

2. What engineering, physics, or scientific principles were demonstrated in the Tower Building experience?

3. Have you done or seen a similar activity before? If yes, what was the activity, and when did it occur?

4. Below, rate from a little (1) to a lot (10) how much you learned or experienced about the following concepts from this activity:

	Learned a little	>>>>>>>>	>>>>>>>>	>>>>>>>>	>>>>>>>>	>>>>>>>>	>>>>>>>>	Learned a lot		
Working in a team:	1	2	3	4	5	6	7	8	9	10
Creativity in design:	1	2	3	4	5	6	7	8	9	10
Prioritizing design goals:	1	2	3	4	5	6	7	8	9	10
The necessity of redesign:	1	2	3	4	5	6	7	8	9	10
Working as a team leader:	1	2	3	4	5	6	7	8	9	10
Working as a team member:	1	2	3	4	5	6	7	8	9	10
Working with limited resources:	1	2	3	4	5	6	7	8	9	10
Operating within time constraints:	1	2	3	4	5	6	7	8	9	10
Considering multiple goals simultaneously:	1	2	3	4	5	6	7	8	9	10
Principles of structures and structural integrity:	1	2	3	4	5	6	7	8	9	10