Using Guided Project and Reverse Engineering to Develop Critical Thinking

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***Abstract* - A project was used in a sophomore Mechanics course as a first step in developing critical thinking for engineering students. At this level, a true open-ended project would be an overwhelming experience for the students because they are not mature enough, from the technical point of view, to develop a successful design process. Guidance and pre-determined supervision help them planning the design process and explore the alternative solutions for the problems. The students were asked to work in small teams (two or three students per team) and perform a reverse engineering for a mountain bicycle to evaluate the optimum performance. The small team size was decided to avoid team dynamics problems and allow the students to focus on the design process. The skill needed for the project was basic gear kinematics which is covered in the course. The additional information in terms of aerodynamics, bicycle dimensions and ground traction was left for the students to research. The subject of the project (bicycle) was chosen to give the students a product they are familiar with and have access to. The project was divided into small tasks with short due dates. Each team of students submitted a solution for each task and was given the correct answer after that to continue to the following task of the project. For each task, sample results, trends and a detailed description of the deliverables were given in the beginning of the project. Based on the assessment data and the student feedback, the project showed success in introducing the students to problem-solving techniques and critical thinking skills.**

Index Terms – Design in Engineering, Mechanical Engineering, Critical Thinking, and Projects.

INTRODUCTION

Critical thinking and problem-solving techniques are two of the core skills for engineers even before selecting the design tool. It is a fact that modern tools such as numerical, experimental, and empirical methods are needed, however the designer's mind that uses them need to be developed first. Engineering schools usually use the first two years of the program to build the foundation of the engineering skills, Math and Science. Then true engineering course are introduced in the junior and senior years where critical thinking and problem solving skills are introduced and reinforced. If these skills are introduced in a reasonable level at the first two years, students will have more time for developing the skills in four years instead of rushing them in two years.

Design projects are good tools to support the development of both technical and soft skills. An open-ended problem is usually the starting point of a project. Level of difficulty, solution tools, timeline, and outcomes need to be well determined based on the objective of the project (technical, soft skills or both) and the level of the students. Capstone senior project is an effective tool that has been used successfully by many Engineering Schools to introduce the Engineering students to a "real world" open-ended problem. In a year-long course they work in teams and design, build, test and deliver a final product to a customer.

Todd et al. [1] summarized survey results for the use of capstone senior project in the mid-nineties. They reported how projects are effective in helping the students to develop soft skills (communication and project management) and also to grow their technical capabilities by learning new design tools. Management tools such as design reviews and technical meeting are main parts of the project. They represent milestones that help the students to find the right path to the solutions. Duesing et al. [2] outlined the main factors for a successful design review meeting and they discussed the effectiveness of using them as mentoring tools for the students. Napper et al. [3] presented how the capstone project can be used as an indicator for the ABET program outcomes requirements.
Introducing the students to multidiscipline open-ended problem is another area where capstone senior projects can be used. For example, an internet controlled robot was designed and built by a team of Mechanical, Electrical and Computer engineering students as a capstone project, Mokhtar et al. [4]. Miller et al. [5] used a multidiscipline team of senior students to complete an industrial sponsored project. Students worked for clients and were given a list of specifications and requirements. Recently, Mokhtar [6] discussed the balance between the student mentoring and the window of creativity in capstone senior projects.

Introducing projects at a different scale throughout the Engineering Program showed also a success. Newell et al. [7] used a project to support a Heat Transfer course. For

Kinematics and Dynamics junior level courses, Leifer [8] used projects where students were asked to design and build a teaching aid for K-12 students. In a Mechanics and Material course, Crone [9] used projects to support the technical content of three to courses in sequence. The focus was the technical aspect of the projects. Mokhtar et al. [10] discussed the use of a research and applied project in a junior level Machine Design course. Projects were also used to meet the "realization" ABET requirements in the Thermo-Fluid area, Mokhtar et al. [11]. Even in the freshman year, projects were used to introduce the students to engineering and to increase their interest in the field, Mokhtar [12]. Project-Based-Learning (PBL) was effectively used to enhance the learning in Engineering Programs, Mokhtar [13], Hadim [14].

PRESENT MODEL

In the present work, a project was used in a sophomore Mechanics and Machines course to introduce critical thinking and problem-solving techniques. The course was redesigned to include an introduction to machine elements (shaft, bearings, gears, belt, etc) beside the basic Mechanics topics. The objective of this re-modeling is to provide the students with some design an analysis tools for the cooperative education courses they are taking in the following semesters.

In the project, the students were asked to work in teams and reverse engineer a mountain bike to estimate the top speed. To guide the students throughout the project, the problem was divided into a list of short tasks. Examples of the trends and results of each task were given to the students in the beginning of the project. The list of tasks was grouped into three due dates where all teams have to complete them and submit the solution. The solution was then posted and the students were allowed to use it to move to the following step in the project. The submitted solutions were given initial grades and returned to the students. This grade was then adjusted based the quality of the responses to the following set of tasks. A final report was required that integrated all these steps.

COURSE OUTLINE

The Mechanics and Machines course is the first course in the machine design sequence. Students from Mechanical, Electrical, and Manufacturing Engineering programs take this course in the sophomore year before a mandatory Cooperative Engineering course. The School of Engineering decided to remodel this course and introduce applications such as keys, shafts, gears, bearings, etc. The objective is to give the students some applied tools before they work for a company during their Cooperative Engineering course. The mechanical applications are integrated in the course content following their relevant conceptual topic. For example, keys are introduced after shear stress, belt are introduced after moment of a force and so on. The application part was taught in a survey form.

Educational outcomes: By the end of the course students will be able to:

1. identify the types of loading in mechanical systems;
2. draw free body diagrams of assembled structures and their components;
3. apply equilibrium equations to determine support and internal loads in structures;
4. calculate stresses in machine components under common loading which is a combination of axial loading, twisting, and bending;
5. utilize the knowledge of stress analysis, materials towards the design of machine elements;
6. design various machine elements using software tools.

As can be seen, except for last objective, all objectives match the classical Mechanics course. The last objective was added for the mechanical parts. The project is addressing the first and the second objectives and partially uses some of the skills covered by the last objective (gear kinematics). It was assigned after a couple of weeks of the beginning of the semester. The last two objectives were addressed by a comprehensive design project that was assigned toward the end of the semester.

PROJECT OVERVIEW

Students were asked to estimate the top speed for a mountain bike. The bike has multiple sprocket settings. A full analysis of the setting was required. The project time was three weeks and was divided into ten tasks:

- Task 1. Draw a Free Body Diagram (FBD) of a bicycle with a rider
- Task 2. Relate the speed of a bicycle to the drag force on the bicycle
- Task 3. Relate the drag force to the propelling force on a bike.
- Task 4. Obtain bike parameters
- Task 5. Relate pedal speed to bike speed.
- Task 6. Relate the propelling force to the effort that applied on pedals
- Task 7. Relate the bike speed to the effort that applied on pedals
- Task 8. Find gear shifting speeds
- Task 9. Determine maximum effort that can be exert on the pedals
- Task 10. Determine how fast can the biker sprint towards the finish line and how should he achieve the speed.

The students were asked to form a team of two or three students. Since team work skills were not the primary focus of this project, it was decided to have small team sizes.

Students are required to submit the solution of the first five tasks after one week and the rest of the tasks are due at the end of the second week. Solutions were posted after each due date. The submitted solution was graded and returned to the students. The last week of the project was for the team to incorporate the corrections into a project final report. Several skills were used in the project such as:

- Strategy to break a complex problem into small tasks
- Assumptions
- Observation
- Research
- Estimation
- Free Body Diagrams
- Analysis and calculations

Figure 1 shows the sketch that was given to the students to perform the static analysis. For consistency between teams, this sketch was made of sub-assemblies to allow the students to create free body diagrams.

Figure 1: A simplified bike sketch.

A starting point:

Since this course is taught in the sophomore year, the problem was simplified to limit the number of factors included in the analysis. The following two assumptions were given to the students:

- Rolling resistance is negligible.
- The bike is moving at a constant speed.

Then the students were given the following four leading questions as the starting point for the project:

1. How is bike speed related to the drag force on the bicycle?
2. How is the drag force related to the propelling force?
3. How is the propelling force related to the efforts applied on pedals?
4. What is the maximum effort that rider can apply?

The ten tasks that were mentioned before help the students generate the answer for the problem. The objective of having these questions and the list of tasks is to teach the students a model of critical thinking and solution planning. Below is the details of each task and its deliverable product.

Task 1 Free Body Diagrams: Figure 1 was given to the students in an electronic format and they were asked to disassemble it and study the forces on the subsystems. Figure 2 shows the drawing submitted by one the teams for this task.

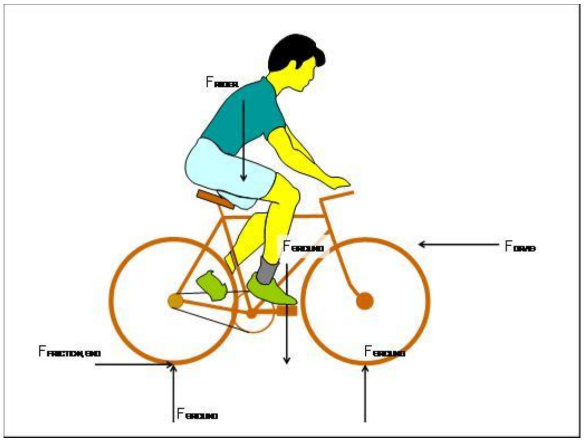

Figure 2: Free body diagram (Student sample).

In the shown sample, the student left the internal load between the rider and the bike, which is not correct. It shows the importance of this first cycle of review before the final submission of the project report.

Task 2 Drag force and bike speed: At this level, the students have limited Fluid Mechanics knowledge and they have to perform significant search to find the relationship between the drag force and the bike speed. They were given the drag coefficient for a mountain bike. Self-learning is an effective tool for teaching and this task introduce the student to this skill. They experience firsthand how to look for a topic with limited knowledge and generate an analysis. Figure 3 shows the a sample of the student work for this task.

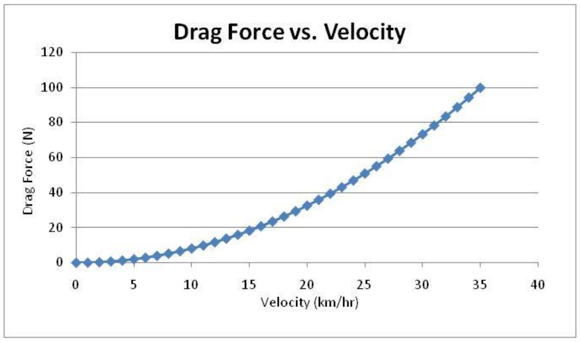

Figure 3: Drag force verses bike speed (Student sample).

Task 3 Drag force and propelling force: The answer for this task seems to be straight forward. The two forces are equal from the free body diagram shown in Figure 2. The propelling force is the traction force between the rear wheel and the ground. Many students tend to put this force opposite to the bike direction of motion because they are used to the dry friction force they learning in the Physics courses. The concept of a traction force that drives the bike is the main purpose of this task.

Task 4 Bike parameters: In this task, the students collect the relevant bike information. They have to decide which information they need and report them. Starting from this task, each team will have its own version of the solution based on the data they collect. Some students reported all dimensions of the bike and some of them were selective and reported only relevant information. Below is a sample from the data one of the teams reported. They organized them in sets for easy reference. Figure 4 shows a photo of one of the bikes used in the project.

- Crank Set

Number of Teeth (N)	48
Radius (R)	11.43 cm

- Outer Most Gear

Number of Teeth (N)	27
Radius (R)	6.35 cm
Gear Ratio	1.8

- Outer Middle Gear

Number of Teeth (N)	24
Radius (R)	5.72 cm
Gear Ratio	2

- Inner Middle Gear

Number of Teeth (N)	21
Radius (R)	5.08 cm
Gear Ratio	2.25

- Inner Most Gear

Number of Teeth (N)	19
Radius (R)	4.45 cm
Gear Ratio	2.5

- Wheels:

Back Wheel Center to Pedal Center	41.28 cm
Radius (R)	30.48 cm
Front Wheel Center to Handle Bars	55.88 cm

- Pedals

Center to Pedal	17.78 cm
Pedal Dimensions	10.16 cm x 10.16 cm x 2.54 cm

Figure 4: A photo of the bike used by one of the student teams.

Task 5 Relate pedal speed to bike speed: With the free body diagrams in task 1, the students can use gear kinematics to relate the pedal speed and the bike speed. This is another skill where students needed to divide a complex system into small components, complete an analysis for each component and carry the information from one analysis to the following one. At this stage (sophomore level), the students are used to be given a simplified system and are asked to solve it. The "big picture" concept is the main objective of this task. The challenge for the students is not to get busy with the detailed calculations of the sub-system and lose the overall line of thinking. Below is a sample from the student work.

N - number of sprocket teeth
n – rotational speed in rpm
R – radius in m
V – linear speed in m/s

$$N_{rear}\, n_{wheel} = N_{front}\, n_{pedal}$$

$$n_{pedal}[rpm] = \left(\frac{N_{rear}}{N_{front}}\right) n_{wheel}[rpm]$$

$$n_{pedal}[rpm] = \left(\frac{N_{rear}}{N_{front}}\right) \frac{60}{2\pi}\, \omega_{wheel}[rad/s]$$

$$n_{pedal}[rpm] = \left(\frac{N_{rear}}{N_{front}}\right)\left(\frac{60}{2\pi}\right) \frac{1}{R_{wheel}[m]} V_{bike}[m/s]$$

RPM	1st Gear	2nd Gear	3rd Gear	4th Gear
100	20.68	22.98	25.85	28.73
80	16.55	18.39	20.68	22.98
60	12.41	13.79	15.51	17.24
40	8.27	9.19	10.34	11.49
20	4.14	4.60	5.17	5.75
0	0	0	0	0

Task 6 propelling force and effort force on the pedals: Using the same free body diagrams, the students are relating the traction force and the pedal force. Figure 5 and 6 show samples from the free body diagrams that one of the teams used for the analysis.

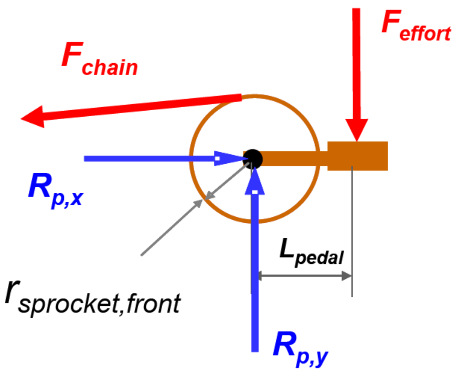

Figure 5: Free body diagram for the pedal (Student sample).

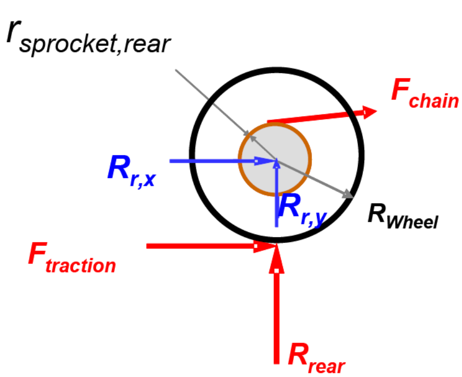

Figure 6: Free body diagram for rear wheel (Student sample).

Task 7 Bike speed to the effort: At this stage, the student can integrate the parameters from the previous tasks. Figure 6 shows a sample of the plots that one of the student teams presented for this task. As shown, the student marked a maximum value for the force and started thinking about the next task which is the gear shift.

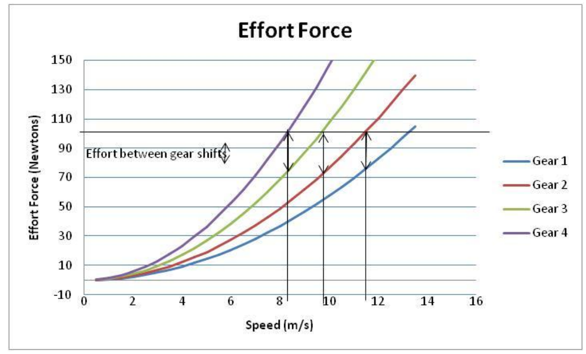

Figure 6: Effort verses bike speed (Student sample).

Task 8 Gear shift: The gear shift is the following challenge for the student teams. It needs some judgment to use the results from the previous tasks and to decide the most appropriate controlling parameter. It could be the maximum propelling speed that a rider can do or the maximum torque that can be applied on the pedal. Figure 7 shows a performance graph generated by one of the student teams. They decided to use a 100 rpm as the maximum propelling speed before the gear shift. The data are presented in another format by a second student team, Figure 8.

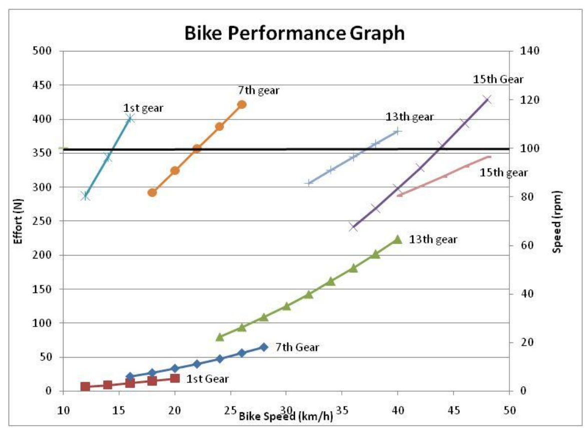

Figure 7 Bike performance (Student sample).

Figure 8 Bike performance, another team (Student sample).

Task 9 Maximum effort: The students were given a set of experimental data where the pedal forces were measured.

Figure 9 shows a plot of the data. The data were obtained in a laboratory activity for another course. The objective is to show the students another source of information (experimental work). Also to let them decide which value can be used for the gear shift. The data were given to the students in table format.

Task 10 Maximum bike speed: The final task it to answer the project question. Figure 10 shows an overall performance graph generated by one of the student teams. The team indicated the maximum bike speed based on the maximum pedal effort (force) and the maximum propelling speed.

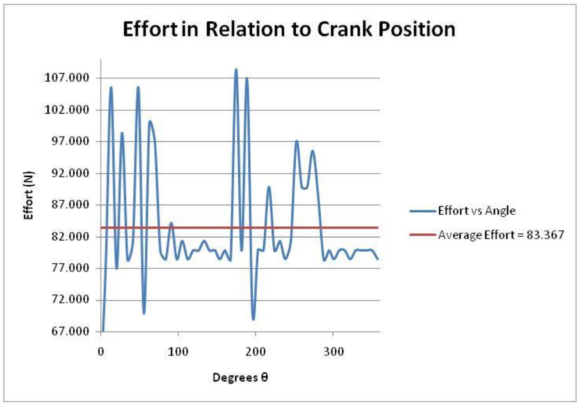

Figure 9: Measured pedal forces.

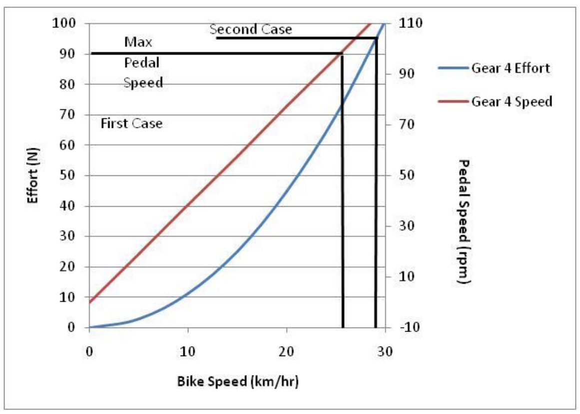

Figure 10: Maximum bike speed (Student sample).

STUDENT ASSESSMENT DATA

In addition to the grading, the students were asked to complete an assessment survey to evaluate the project. Four aspects of the project was assessed:

1. Technical level
2. Amount of work
3. Team work skills
4. The guidance and the critical thinking.

Figure 11 shows the survey results. The student rated all aspect of the project between 70 to 80%. Figure 12 shows the grades of the students for the project. The data is presented in scattered format instead of the normal distribution because the focus here is the general trend not the average value. Both the students survey results and the grades indicate the success of the method. The class size was 31 students. The student got a grade between B and A. Nearly all the student completed all the ten tasks. The grading was based on the initial grade of the tasks and the final report of the project.

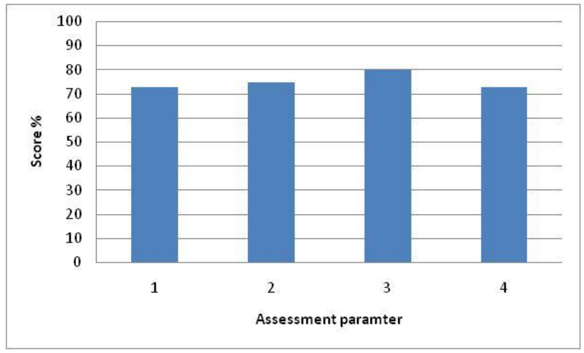

Figure 11: Survey results for the project

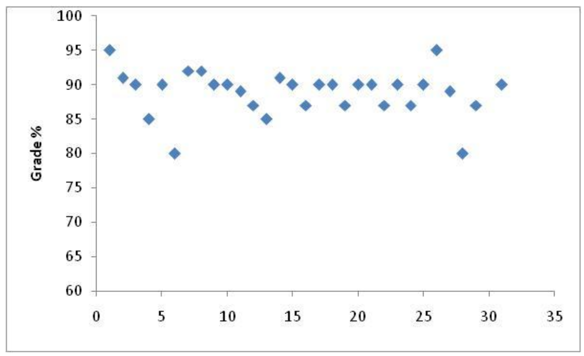

Figure 12: Student grades

CONCLUSIONS

A guided project was implemented in a Mechanics and Machine course. The philosophy is to provide the students with a set of small tasks that help them develop engineering problem-solving and critical thinking skills. Reverse Engineering was used in the analysis of the project components. The details of the project were presented and discussed. The feedback from the student and the assessment data indicated the success of the approach. In the beginning phases of the project the student was focused on completed the tasks in hand. As the project evolves they started to see the “big picture” and understand the purpose of earlier tasks.

Communication skill used in the project was writing only and they were not the main focus. Also, team dynamics was not significant in this project. These factors together allowed the students to focus on developing the critical thinking skills and problem-solving techniques. A Mechanics and Machines course with the remodeled format showed to be a good place to integrate these skills.

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