HYDROELECTRIC PLANT DESIGN AS A SYNTHESIS FOR AN ENGINEERING TECHNOLOGY CURRICULUM

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Abstract

Hydroelectric plant design is an involved process that includes dealing with hydrology, fluid mechanics of open and pressure conduits, turbomachinery, economics, and electrical power generation. This process involves an economic trade-off condition between capital cost and possible profit from electricity generation; this is an implicit optimization problem. Due to the nature of these types of designs, hydroelectric plant design involves a great deal of engineering judgment. Enhanced ability to make engineering judgments is one desired outcome of any engineering or engineering technology program. This paper deals with a design problem for students in a fluid power course within an engineering technology curriculum and shows the benefits of a final project and that requires some engineering judgment.

Introduction

How do we prepare students for a work environment, when classes are often highly structured and their future work environment is often fraught with ambiguous situations that call for spur-of-the-moment judgments? How do we instill engineering judgment in students? Teachers need to go beyond just giving the students a set of tools to be utilized for a broad set of circumstances by actually showing the students when to use a certain tool, which is the beginning of engineering judgment.

This proposed approach to address these issues was to teach a fluid-power class, during a fourteen-week semester, in the following manner. The class began with ten weeks of fluid mechanics, beginning with a basis in conservation of energy, mass, and momentum. The course then went on to discuss fluid statics, pipe flow, minor losses, pump design, and turbine design. The final four weeks were devoted to the design problem and used a series of four reports on the design of critical elements of a hydroelectric plant. The skills taught by the hydroelectric plant design are:

1. The first skill that is generally conveyed is that the initial design is based on an estimate, a guess as the students would put it.
2. Integration of economics, power concepts, and optimization is required.
3. An optimization is performed to find the trade-off condition between capital cost for the penstock versus head-loss that affects the present worth analysis.
4. Use of non-dimensional analysis.
5. Using Excel to determine head-loss in penstocks.
6. Determination of specific speed, turbine type and wheel diameter from the Cordier's diagram.
7. Understanding efficiency
8. Engineering judgment

The outline of this paper begins with a background section that explores the nature of manufacturing engineering technology at Nicholls State University, followed by the educational outlook of the authors, and the fluid power class used for this study. The hydroelectric plant design will then be discussed followed by a presentation of a survey and its results. These results, along with the study, are discussed and conclusions made.

Related Research

The manufacturing engineering technology program at Nicholls State University Our manufacturing engineering technology program is built around a core series of project courses that serve as the capstone-manufacturing experience requiring implementation of the technical and business management courses. The novelty of these project courses is that the students from three grade levels (senior, junior, and sophomore) participate in the projects. This approach provides both horizontal and vertical integration of the design/manufacturing project, which is not common [1]. Students register for the appropriate sophomore-, junior- or senior-level project course, but they all meet together and are administered under the same course structure.

The students are divided into several teams with each team functioning as a division in a small company [2-4]; each team participates in a two-semester-long project. The tasks assigned each class level are designed to be compatible with the courses that a typical student should have completed or be taking at the sophomore, junior, or senior levels. Each student gets experience at his or her level of education with the most intense and demanding load being placed on the seniors. The intent of this project approach was to give the students a more realistic engineering experience while they are still at the university so they will be better prepared for their first real-world experiences. Additional approaches that allow the faculty to meet student-learning needs are also being considered. In so doing, the authors have chosen two courses in which to explore some of the relevant teaching and learning theories were believed to be particularly applicable to engineering technology curricula. The theories are

(1) Piaget's intellectual development theory, (2) scientific learning cycle, and (3) Kolb's learning and teaching cycle [5]. A brief discussion of these theories follows.

Educational Outlook

Piaget's theory discusses the stages of intellectual development from new-born to adult. But this study was only concerned with the concrete-operational and formal-operational stages, and the transition from the former to the latter. The concrete-operational stage addresses the ability to do mental operations only with real (concrete) objects, events or situations. The formal-operational stage relates to being able to think abstractly; formulate hypotheses without relating to real objects, events or situations; testing hypotheses and logical alternatives; and generalizing from real objects to abstract notions and ideas. At the formal-operational stage, the student is capable of learning higher math and is capable of applying it to the solution of new problems. Engineering technology education requires at least some ability to operate at the formal-operational level. Students operating at the concrete-operational level learn math by memorization and are usually unable to use it to solve new or unusual problems and, consequently, will have difficulty with an engineering type of curriculum.

Piaget felt that the transition from concrete operational to formal operational was complete by the twelfth year, but more recent studies [6], [7] have shown that as much as 60% of the adult population appears to still be in the transitional stage between the two phases. That is, they can sometimes use formal operational thought, but not always. Experience shows that many of our engineering technology students are in the transition between the concrete- and formal-operational stages of intellectual development. A critical question is "How do we help our students move more toward formal operational intellectual development"? Piaget proposed that the transition is initiated by the introduction of new ideas that don't fit the individual's current mental structures, thus creating a disequilibrium that the individual must deal with in some way. The new ideas may be dealt with by rejecting them or, if they must be dealt with, they are memorized but not understood—this is often what the concrete-operational individual does—if they are not too dissimilar, they may be accommodated into the existing mental structure, if they are quite different from the existing mental structure they may be transformed to fit the mental structure or, ideally, the mental structure is changed and grows to be able to assimilate these new ideas. As the assimilation occurs, the individual's intellectual development stage becomes more formal operational and less concrete operational. Two well-known learning cycles have been proposed that have the potential to create the needed disequilibrium and help guide students in assimilating the new ideas. They are the Scientific Learning Cycle and the Kolb Learning Cycle. Each will be discussed briefly.

The Scientific Learning Cycle is a three-stage cycle. The first stage is an exploration_or self-discovery phase where students explore a new phenomenon with minimal guidance and try to learn how it works by using it. The exploration phase could involve computer simulations to explore a process or device. Phase two is called the term-introduction or invention phase, or the concept-invention or introduction phase where the instructor fills in the parts the students missed in the exploration phase. And, finally, the concept-application or expansion phase where students apply the new ideas, terms, and/or patterns to new examples by homework, discussion, laboratory exercises, etc. This learning cycle is simple and straightforward in principle, but can take a great deal of preparation by the instructor to have a properly designed self-discovery phase.

The Kolb Learning Cycle is similar, but is based on the idea of two dichotomies considered to be orthogonal to each other. The first dichotomy addresses how individuals transform experience to knowledge and contrasts Active Experimentation (AE) with Reflective Observation (RO). The second is Abstract Conceptualization (AC) versus Concrete Experience (CE) and addresses how individuals grasp or take in knowledge. The two dichotomies are arranged at the extremes on orthogonal axes called Processing Information (horizontal axis) and Taking in Information (vertical axis), as shown in Figure 1.

Complete learning demands that all four stages or steps be covered. And although one may enter the cycle at any point, the most common point to enter is at CE where personal involvement is required. For complex information sets the cycle may be traversed several times in an upward spiral progression. There may be attempts to short circuit the cycle by skipping steps, but this results in incomplete learning. Retention of information as a function of the steps completed is assessed as follows: (1) AC only-20%, (2) AC + RO-50%, (3) AC + RO + CE-70%, and AC + RO + CE + AE-90%. An example of a complete and reasonably good teaching cycle to match the learning cycle would be lecture (RO) followed by requiring that the students think about the ideas presented (exactly how to do this might cause questions) (AE) and then homework (CE) followed by a required laboratory experiment. Lecture (RO) followed only by homework (AE) is not very good. In a continuing emphasis on team work and communication, both written and oral reporting, and most assignments, will require working in teams so that student interactions will aid the learning process and students will develop the ability to communicate and work in teams.

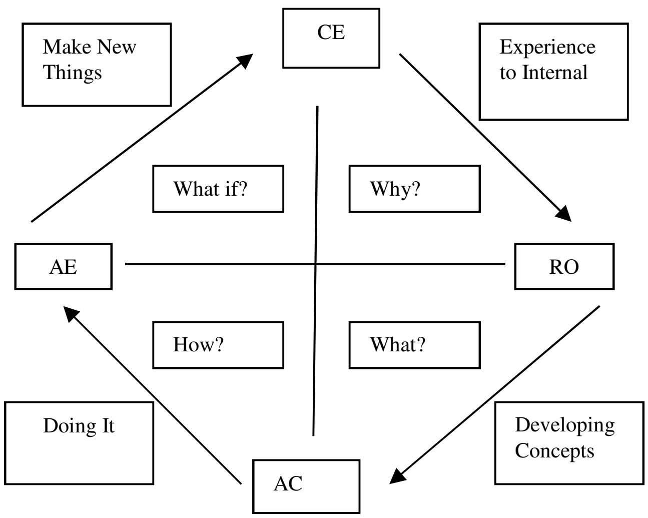

Figure 1. Modified Kolb Learning Cycle

It is also desirable to take the students through all stages of the learning cycle by carefully chosen lectures, often occurring in a just-in-time manner: discussions, discovery experiences, working in teams, analyzing, synthesizing, building, and testing. This emphasis on systems will allow both analyses and syntheses.

The full Kolb Learning Cycle was not employed in this experience, but most of it was followed and, in fact, the scientific learning cycle was approximated very closely. The point is that the first author was involuntarily following some of the principles discussed above. If we use the Kolb Learning Cycle (see Figure 1), he began at the point labeled RO. Through lectures, homework and exams, the students developed abstract conceptualization, AC. After the fact, the laboratory experience brought the students to CE, which occurred throughout the semester. "After the fact" in this case means that motivation should precede all new material, which will be further developed in the discussion.

The final project brought the students toward AE and through to CE. The students did go through the complete cycle because several projects were assigned and completed with minimal guidance. The remainder of the paper describes the details of the approach taken in this attempt to apply the scientific learning cycle method.

Fluid Power and Fluid Power Laboratory

Fluid Power is essentially a fluid mechanics class with an emphasis on hydraulic machines that can do useful work [2], [4], [8], [9]. The class was taught as fluid mechanics with an emphasis on pumps and turbines. Several weeks were devoted to pumps and turbines.

The final four weeks were devoted to designing critical elements of a hydroelectric plant. This project was useful for several reasons. It brings home a plethora of fluid mechanics concepts that all have to be mastered in order to develop a successful design. It integrates engineering economics for a successful design. More importantly, it cultivates engineering judgment.

Problem Statement

The hydroelectric plant design involved four reports. The first was an initial economic design based on a capital cost, annual benefits from electricity generation, and other costs. The second report was the design of a penstock, involving a trade-off condition between capital costs and head-loss. From this second design, five scenarios were determined: 25, 30, 35, 40, and 45cm diameter penstocks. The third report was the design of a turbine and determination of its cost. The fourth report was a final economic analysis with better estimates of the capital costs for the three scenarios.

This section shows the required work delineated into four sections. Figure 2 presents a conceptual model of the hydroelectric plant.

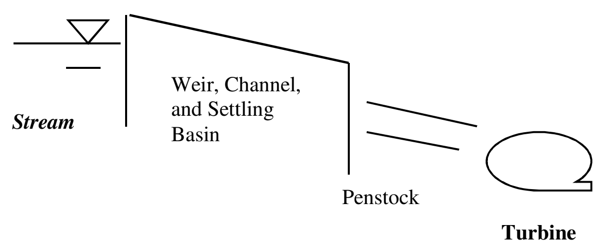

Figure 2. Diagram of Hydroelectric Plant

This was a four-week project to design critical elements of a hydroelectric plant. It should be noted that this design was not complete. Each Friday by close of business a 5-page report would be due. The requirements of each report are given below.

Preliminary Design

1. Determine kWh's produced
2. Determine annual benefits
3. Given useful life of 12 years and the following cost data, is this a viable project at a marginal rate of return (MARR) of 10%? See Table 1.

Table 1. Initial Design Information

Capital Cost	$285,000
Annual O&M	10% of Capital Cost
Salvage Value	10% of Capital Cost
N	12 years
Electricity Sale Value	$.06 per k@-hr.
MARR	10%

Penstock Design

1. Given a length of 610 meters, determine an optimal D
2. Determine head-loss for penstock (use 5%, 10%, 15% and 20%) and determine diameters
3. Determine cost of penstock given steel is $.25 per Newton, which is the cost of the material, emplacement, and supports

Turbine Design

1. Determine N_S given Q = .30 m^3/s, Total Head is 91.5 meters, and N = 600 rpm. Determine H(a) from penstock head-loss and assume 5% head-loss for weir and channel. An approximate value can be that the available head is 85% of the total head.
2. Determine appropriate turbine type from Table 3.2 in handouts (provided to students)
3. Determine D_S from Cordier diagram
4. From D_S, determine D for the wheel
5. Determine the blade angle and nozzle diameter
6. Given head-loss for weir, channel, penstock, and 10% for turbine, and 10% for generator and electrical transmission, determine kW's produced (see Table 2)
7. Determine turbine cost from handout

Table 2. Efficiencies

ε(weir)	95%
ε(channel)	
ε(penstock)	To be determined
ε(turbine)	90%
ε(electrical)	90%

Final Design

Recalculate the cost analysis for various head-loss cases and turbine cost using Table 3. Note that each case was a different penstock inner diameter and results in different values for Penstock, Turbine, Generator, and Turbine House costs.

Table 3. Cost Information

	Case 1	Case 2	Case 3	Case 4
Civil Works	$25,000	$25,000	$25,000	$25,000
Penstock	TBD	TBD	TBD	TBD
Turbine	TBD	TBD	TBD	TBD
Generator, Turbine House	Same as Turbine	Same as Turbine	Same as Turbine	Same as Turbine
Misc. Cost	$20,00	$20,00	$20,000	$20,000

Methodology for the Design

Initial Design

From Table 4, the students discerned that the project may be viable and they proceeded to the next step, which was the penstock design. The students had to estimate capital costs and efficiency (ε) in order to calculate the benefits derived from power generation. This leaves the students uncomfortable because essentially this initial design is a guess. This guess is a step in the direction of engineering judgment.

Table 4. Initial Design

Q (cms) =	.30
HT (meters) =	91.5
Capital =	$285,000
N (years) =	12
Sale ($/kW-hr)	0.06
O&M	10%
Salvage Value	10%
MARR	10%
Efficiency (ε)	50%

Power Generation	
Power (kW) =	135
E/yr (kW-Hr)	1180759
Benefits	70846
Annual O&M	$28,500
Salvage Value	$28,500
Present Worth (10%) =	$21,691

As can be seen in Table 4, the initial design is a viable option at a marginal rate of return of 10% with a present value of $21,691. It was assumed that the overall efficiency of the plant was 50% and would have a useful life of 12 years.

Penstock Design

The penstock design (Table 5) is a difficult element of the project because there is a trade-off condition between the size of the penstock and the associated capital cost versus the head-loss and power efficiency. Having the students deal with trade-offs and comparing engineering and economic considerations was another important lesson.

As expected, increasing the pipe diameter reduced head-losses, but also increased capital costs. It was found that the optimal diameter to maximize the final economic analysis (see Table 7) was .35 meters.

Table 5. Penstock Design

Diameter (m)	0.25	0.3	0.35	0.4
HL (m)	65.9	26	11.9	6.1
D (Inner) (m)	0.25	0.3	0.35	0.4
D (Outer) (m)	0.26	0.32	0.37	0.42
A (m^2)	0.005	0.007	0.01	0.013
V (m^3)	3.07	4.42	6.02	7.86
Weight (N)	236,914	341,157	464,352	606,501
Cost	59,229	85,289	116,088	151,625

Turbine Design

The turbine design is based on the Cordier Diagram, which is discussed by Logan [4]. The Cordier Diagram is a means of determining the most efficient non-dimensional diameter (Ds) for a specific speed (Ns). Given Ds, the ideal diameter of the turbine can be determined. Based on Ns, the most efficient type of turbine can also be determined where Pelton Wheel is (.03-.3), Francis Turbine is (.3-2.0) and Kaplan Turbine is (2.0-5.0). The analysis is given in Table 6. Figure 3 gives cost data for Pelton Turbines [9]. For brevity, information for Ds and appropriate wheel diameters are not given in Table 6.

Table 6. Turbine Design

H (a) "m"	21.03	60.93	75.03	83.53
N (rpm)	600	600	600	600
N	62.83	62.83	62.83	62.83
N(s)	0.63	0.28	0.24	0.22
Type	Francis	Pelton	Pelton	Pelton
Power (kW)	50	145	179	199
Cost	55,140	79,822	97,811	108,656

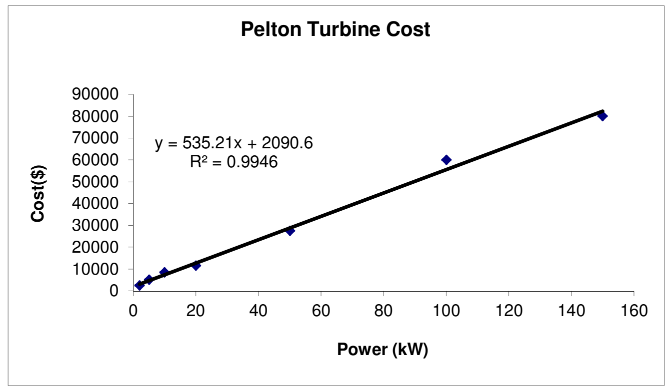

Figure 3. Turbine Cost [5]

Final Design

The final design is given in Table 7 and the present worth of each option is shown in Figure 4. In Figure 4, the options investigated were a penstock with .25 to .50 meter diameters. It is obvious that .35 meters is the best diameter to maximize the present worth.

Table 7. Economics

Case	0.25	0.3	0.35	0.4
Weir	5000	5000	5000	5000
Channel	20000	20000	20000	20000
Penstock	59229	85289	116088	151625
Turbine	55140	79822	97811	105211
Generator	55140	79822	97811	105211
Etc.	20000	20000	20000	20000
Capital Cost	214508	289933	356710	407047
e(overall)	19%	54%	66%	72%
Power (kW)	50	145	179	193
Price	0.06	0.06	0.06	0.06
Benefits	26372	76419	94105	101380
PW	-174142	42450	52806	19344

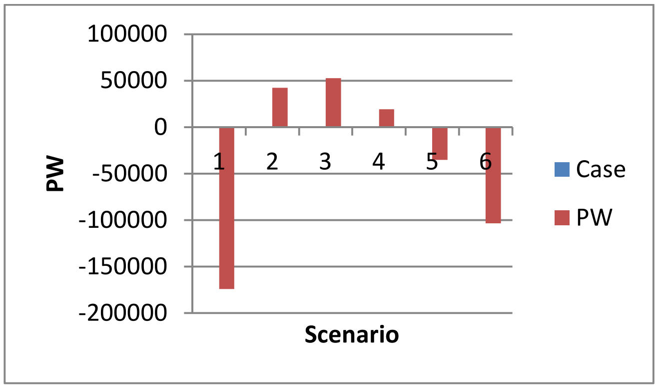

Figure 4. Present Worth Analysis

Discussion

Surveys were given before the last four weeks of class and during the last week of class.

Questions asked included:

1) What do you like best about this class?
2) What do you like least about this class?
3) How well is the teacher doing?
4) How well are you doing in this class?
5) How well is your team functioning?
6) Is the course load just right, too much work, or too little work? Where {1,2,3} is too little, {4,5,6,7} just right, and {8,9,10} too much.
7) How well do you feel you know the material?
8) What is your overall rating of this class?

The results of the survey for questions 3 through 8 (which have quantitative values) are given below in Table 8. These results will be commented on in the Discussion section.

Table 8. Survey Assessment, where 1 is the worst and 10 is the best

	Q3	Q4	Q5	Q6	Q7	Q8
Before (n = 7)						
Average	6.9	7.1	7.7	6.9	6.4	6.4
Standard Deviation	1.2	1.5	1.9	1.1	1.5	2.0
After (n = 3)						
Average	8.0	8.7	9.0	6.0	8.3	8.0
Standard Deviation	0.0	0.6	0.0	0.0	0.6	0.0

As can be seen from Table 8, the students felt by the end of the last four weeks of the semester that the teacher was doing better, they were doing better, their team was functioning better, the class had gotten slightly easier and that they had a firmer grasp on the material and rated the class highly. It is interesting to note that in both the 'before' and 'after' surveys, the students indicated that they were doing better in the class than the teacher. This may be particular to the class or it may be particular to student psychology.

The results of this survey have to be questioned, especially given that the 'after' survey only included three students in the population and these were likely better students. These better students would bias the results. Also, are the results of the survey statistically significant?

Other observations from this class include: trade-off conditions are the basis to optimization problems and should be presented to the students early on, because many of their work designs will involve some form of tradeoff; the students did not like the quizzes, which was one of the best assessment tools; the students tended to enjoy the hydroelectric plant design project, which was open-ended, because it allowed them to provide unique solutions.

It needs to be discussed that the hydroelectric design involved some simplifications that should to be addressed. The assumed efficiencies for the weir, channel, settling basin, turbine and electrical generation need to be explored in an actual design; the electrical components of the system were ignored, but are very important; cost data was from 1990 and an actual design would involve vendor quotes for equipment and services; and, the sales cost of electricity generated would have to be assessed for the area where the electricity was generated.

Further Research

The fluid power course utilized for this work was a course with a problem-based learning pedagogy. The hydroelectric plant design utilized in this paper is one possible final project. Other final projects could be the design of a pump/pipe system that includes a cost estimate, other aspects of a hydroelectric plant not covered in this work, or a compressor/pipe system design with detail cost estimations.

Future educational research papers could explore how an instructor presents an open-ended final project and guides the students through the project, while having the student's take ownership of the work. One idea on how this could be done is to provide the students with an RFP of work, have the student groups propose the work, have the instructor act as the party asking for bids and limited to the knowledge that party would have, and have a third-party act as a senior engineer to guide the students through the project.

Conclusion

There is some benefit to utilizing an end-of-the-semester, open-ended problem that incorporates many seemingly disparate ideas and utilizes a systems approach. The benefits include: allowing the students to discover engineering concepts, which empowers them; synthesis of many ideas; for this particular problem, incorporation of economics and explicitly addressing the trade-off of capital cost versus yearly revenues from power generation.

Better assessment tools need to be utilized. A more thorough method of assessing teaching and learning methods is being conducted in the upcoming semester. Assessment includes several surveys throughout the semester (both written and oral). The oral surveys will be conducted by a student who has taken the class. Utilizing graded homework and tests to assess different approaches to learning and teaching methods, and a final project to bring it all home.

References

[1] Alabart, J.R., Herrero, J., Giralt, F., Grau, F.X., and Medir, M., "Two Way Integration of Engineering Education Through a Design Project," *Journal of Engineering Education,* April 2000, pp. 219-229.

[2] Foust, Henry (2005). Class notes for EGTC 245 and EGTC 246; Nicholls State University.

[3] Humphreys, M.A., Meier, R.L., and Williams, M.R., "Refocusing Our Efforts: Assessing Non-Technical Competency Gaps," *Journal of Engineering Education*, July 2000, pp. 377-385.

[4] Logan, Earl (1993). Turbomachinery: Basic Theory and Applications. Marcel Dekker, New York, NY.

[5] Pavelich, M.J. (1984). "Integrating Piaget's principles of intellectual growth into the engineering classroom." *Proceedings ASEE Annual Conference*, ASEE Washington, DC, 719 to 722.

[6] Pintrich, P.R. (1990). "Implications of psychological research on student learning and college teaching teacher education" in W.R. Houston, M. Haberman, and J. Sikula (Eds.), Handbook of Research on Teacher Education, MacMillan, New York, 926 to 857.

[7] Granger, Robert (1995). Fluid Mechanics. Dover Publishing; New York, NY.

[8] Harvey, Adam (1993). Microhydro Design Manual; Intermediate Technology Publications, Bourton-on-Dunsmore, Rugby, UK.

[9] Roberson, J. and Crowe, C. (1997). Engineering Fluid Mechanics; John Wiley and Sons; New York, NY.

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