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## **AC 2012-4396: INTEGRATION OF SYSTEM THINKING, ENGINEERING REASONING, AND DECISION-MAKING SKILLS IN DESIGN OF THERMAL SYSTEMS COURSE**

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# **Integration of System Thinking, Engineering Reasoning and Decision Making Skills in Design of Thermal Systems Course**

## **Abstract**

Design of thermal system is in essence a Capstone design class for thermal and energy systems. One of the major difficulties encountered by instructors in these Capstone design courses is that many senior students do not have adequate preparation in applying design skills such as critical thinking, engineering reasoning, and decision making to successfully complete their design project. In this paper, the process of integrating system thinking, engineering reasoning and decision making skills into Design of Thermal Systems course is described. The paper includes several class activities to integrate these skills, impact of these activities on student learning and design skills, assessment and evaluation of students' skills, and rating of students on these skills in relation to engineering design.

## **Introduction**

A Capstone design class is a required course to complete engineering degree requirements for senior students in all engineering disciplines. Students are divided into design teams and each design team is required to complete design of an engineering product or system. Design of thermal system is in essence a Capstone design class for thermal and energy systems. One of the major difficulties encountered by instructors in these Capstone design courses is that many senior students do not have adequate preparation in applying design skills such as critical thinking, engineering reasoning, and decision making to successfully complete their design project<sup>1, 2, 3</sup>. These skills are higher level cognitive skills known as application, analysis, synthesis, and evaluation according to Bloom's Taxonomy<sup>4</sup>.

Current engineering curricula are generally concentrated on providing the students with lower level cognitive skills: namely, knowledge, comprehension, and application, through sophomore and junior level mathematics and engineering science courses leading up to the senior level. The curricula implicitly assume that students who become proficient in these lower level cognitive skills will be able to apply high level cognitive skills in the senior classes, especially design and Capstone design classes. Unfortunately, it was not the case for many senior engineering students. It is essential that engineering students develop the generalizable critical thinking skills and disposition necessary for effectively and professionally reasoning through the complex engineering issues and questions they will face as engineers<sup>5</sup>.

Similar conclusions regarding system and system thinking were drawn much earlier by Stoecker in his book<sup>6</sup>. Under the heading of system, he stated that engineering education is predominantly process oriented, while engineering practice is predominantly system oriented. There is a big gap between knowledge of individual processes and the

integration of these processes in an engineering enterprise. He recommended in his book that it was beneficial for future engineers to begin thinking in terms of system.

In problem solving and engineering design, decision making is essential based on mastery of engineering knowledge and practical engineering experience. Morris<sup>7</sup> describes the step-by-step decision making process as consisting of the following steps.

- Describe the problem.
- Define the objective.
- Consider the facts and factors.
- Choose the best solution.
- Use horse sense.

These five steps are in general the same as those involved in an engineering design process. In each step of engineering design, decisions must be made to achieve the satisfactory or optimal design solution. Engineering is one decision after another<sup>7</sup>. As a result, an engineering student must learn to acquire decision making skills during his studies.

In this paper, the process of integrating system thinking, engineering reasoning, and decision making into Design of Thermal Systems course will be described. The paper includes several class activities to integrate these skills, impact of these activities on student learning and design skills, assessment and evaluation of students' skills and the rating of students on these skills in relation to engineering design.

### **Design of Thermal Systems Course**

MEEN 4313 Design of Thermal System course is a required course for the senior mechanical engineering students at Lamar University. The course is offered in every fall semester and consists of 30 lecture periods of 90 minutes each. It is the culminating course for thermal fluid stem where synthesis of junior and senior level classes is presented with respect to real-world engineering systems such as a coal-fired power plant. The course covers design process, equipment selection, economic consideration, mathematical modeling, and numerical simulations of energy systems. More detailed description of the course was presented in an earlier paper<sup>8</sup> by the author. After teaching the course for four years, the author decided to integrate system thinking, engineering reasoning, and decision making activities into the course based on two main reasons: the first is the results of the student evaluations that reflect the difficulties encountered by students in synthesizing and applying the engineering science knowledge on design of thermal systems, and the second is lack of computer-based system simulations in the previous course content. As a result, the course content and emphasis have changed into five main areas:

- Engineering design process and system thinking
- Selection and design of components of thermal systems
- Engineering economics and life cycle cost analysis

- Mathematic tools for simulation of thermal systems
- Computer simulation of thermal systems

Each will be discussed in details with sample activities of system thinking, engineering reasoning, and decision making skills.

### Engineering design process

The design process is the main emphasis in this part of the course with system thinking and critical thinking being the major skills integrated into the delivery of engineering design process.

Three lecture periods are spent on the topic of engineering design and design teams supplemented by some reading materials. The first lecture is devoted to engineering design and design methodology. Two different definitions of design are given according to the Merriam-Webster dictionary and ABET. One of the definitions of design given by Merriam-Webster dictionary is “**the DESIGN and MANUFACTURE of complex products**”. In contrast, the definition of engineering design by Accreditation Board for engineering and technology (ABET) is provided: Engineering design is the process of devising a system, component, or process to meet the desired need. Extensive discussions on the two definitions are conducted in class with examples of engineered products such as razors, computers, and automobiles. Importance of iterative nature and decision making of engineering design as well as the roles of design objectives and criteria to implement and evaluate the design are discussed. Next, the needs for design and different types of design solutions are discussed. For example, design solutions are classified into four classes according to Boehm<sup>9</sup>: non-function, functional, satisfactory, and optimal design. Several in-class activities for the students are given to reinforce the concept of design and provide critical thinking skills. A sample activity for student is to compare an old single-blade razor with the new and modern five-blade razor shown in Figure 1. The students are to identify the changes between the two razors considering materials, manufacturing process, aesthetic, etc., and provide some reasons for these changes.



**Figure 1 Engineering comparison of two razors**

The last part of the lecture introduces students to the steps typically involved in an engineering design process together with the importance of developing a proper problem statement considering customer requirements or needs, engineering specifications, constraints, and design criteria. A brief introduction to the engineering standards and codes are given too.

Design of thermal systems is in many ways different from the design of mechanical systems. As a result, the second lecture is devoted to the design of thermal systems together with an introduction to system thinking. Definition of system and systems thinking are discussed with emphasis on examples from thermal systems. A system is an interconnected set of elements that is coherently organized in a way that achieves something<sup>10</sup>. Engineered products and thermal systems fit nicely into the definition of system as given above because typical engineering systems consist of components and sub systems that are interconnected and interact with each other, and they are designed to serve a specific need or purpose. For example, a steam power plant in its most simple configuration has four subsystems: a pump sub-system, a boiler sub-system, a turbine sub-system and a condenser sub-system. The condenser sub-system consists of individual components such as one or more condensers (heat exchangers) as well as pumping systems for both hot and cold fluids. The primary message of systems thinking is that a system is more than the sum of its part and that it is essential to consider the interactions (effects) among components of sub-systems and system itself. A You-Tube video on system thinking by Dr. Russell Ackoff<sup>11</sup> is used to introduce the mechanics of systems thinking. Definition and characteristics of thermal systems are discussed next using a cooling system for automobiles. Students are asked to identify the following from the exercise:

- Identify sub systems.
- Identify components of sub systems.
- Identify for each component, the design variables.
- Identify other parameters for the system.
- Identify ways each subsystem or component interacts.
- How do you model and simulate the system?

The main goal of the lecture and the exercise is for students to realize the importance of system thinking when devising an engineering design process. In addition, the exercise reinforces specific nature of thermal systems as opposed to mechanical systems such as working fluids and their properties, operating conditions such as temperature and pressure, and their effects on the components, sub systems, and fluid properties. At the end of the lecture, the students are given the following homework:

*Consider the cooling systems for an automobile and a notebook computer. Discuss the differences between the two systems in terms of system requirements, system components, design variables, and constraints.*

The reading assignment on the topic of design for students is to read the document on the design of General Electric (GE) H-turbine system<sup>12</sup> and submit a memo identifying and discussing the design process, rationale for design changes, testing and validating the design.

The last lecture on this part deals with formation of design team, importance of teamwork skills and understanding of team dynamics. In addition, responsibilities of an engineer as a professional are discussed in terms of codes and standards, ethics, and impact on society.

### **Selection and design of components of thermal systems**

Many thermal systems share common components such as pumps, fans, compressors, heat exchangers, turbines, etc. Six lecture periods are used to discuss selection and design of pumps, fans, compressors, heat exchangers, cooling towers, and turbines. The materials related to pump selection and design will be discussed here due to space constraints of the paper.

Pumping systems are found in many applications such as agricultural, residential, commercial, industrial, petrochemical, and waste water systems. According to Hydraulic Institute<sup>13</sup>, pumping systems account for nearly 20% of the world's electrical energy demand and 25 to 50% of the energy usage in certain industrial plant operations. The discussions on pumps and pumping systems include the followings:

- Types of pumps
  - Dynamic pumps
  - Positive displacement pumps
- Pumping systems
  - Static head
  - Dynamic head
  - Total head
- Pump selection
  - Specific speed
  - Pump curve
- Affinity laws of pumps
- NPSH and cavitation
- Pump configurations
  - Parallel
  - Series

The student exercises include comparison of features of dynamic and positive displacement pump, and suitability of these pumps for specific application. For example, students are asked to identify a suitable pump for material handling and specific fluids. In addition, the discussions on pump selection emphasize the need to consider not only technical aspects but environmental aspects (emission), reliability aspects (lubrication),

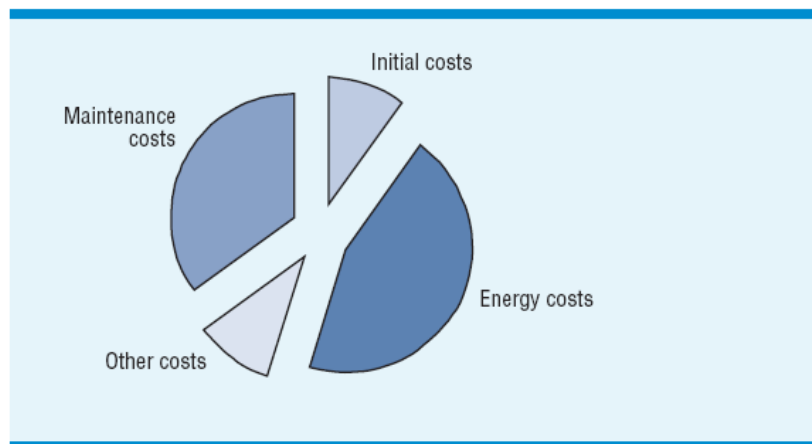
safety (Underwriter Lab label), etc. A few examples of engineering reasoning and decision making exercises in the component selection are given below:

- What are the differences and similarities between fans, compressors and blowers?
- Why does a typical machine shop use a reciprocating compressor rather than an axial compressor? Give specific reasons.
- If a shell-and-tube heat exchanger is used in an automobile cooling system, what are the advantages and disadvantages? Do you recommend using the shell-and-tube heat exchanger in your car?

The section ends with an exam consisting of a closed book part and an open-book part. The closed-book part consists of questions related to conceptual understanding of different thermal components and the open-book portion deals with the selection of pumps, fans, and heat exchangers based on design sheets from manufacturers of these components.

### **Engineering economics and life cycle cost analysis**

Economic analysis and cost estimation are intrinsic to the engineering design process and this section covers both topics. Life cycle cost (LCC) analysis is introduced after the two topics in this section. The life cycle cost (LCC) of any piece of equipment is the total “lifetime” cost to purchase, install, operate, maintain, and dispose of that equipment<sup>13</sup>. A typical life cycle cost for a medium-size industrial pump is shown below in Figure 2. An important point to note from Figure 2 is that the initial (purchase) cost is relatively a small portion of the life cycle cost of the pump. As a result, it is essential to conduct LCC analysis to compare alternative design solutions during the design process.



**Figure 2 A break-down of costs for a medium-sized industrial pump<sup>13</sup>**

At Lamar University, engineering economics is a required course for sophomore engineering students so all the senior students in the design of thermal systems courses are familiar with engineering economic topics such as time value of money, rate of

return, and payback period. Four lecture periods are devoted to covering these topics. For engineering economics, materials from different textbooks<sup>6,9</sup> are used and cost estimation is based on the materials from Boehm<sup>9</sup>.

Life cycle cost analysis is relatively new to the students so materials from several sources are utilized. The primary source is “Pump Life Cycle Costs: A Guide to LCC Analysis for Pumping Systems” published by Hydraulic Institute<sup>13</sup>. It is the result of collaboration between the Hydraulic Institute, Europump, and the US Department of Energy’s Office of Industrial Technologies (OIT). The document contains detail description of how life cycle cost analysis is conducted using a sample case study of a pumping system. In addition, additional reading material on LCC analysis<sup>14</sup> is provided as further reading for students. In terms of assessing the materials, the students are asked to demonstrate their understanding of cost estimation and LCC analysis by conducting LCC analysis in their group design project to be described later.

### **Mathematic tools for simulation of thermal systems**

In this section, ten lecture periods are used to cover curve fitting, fluid properties, modeling of components and thermal systems, and solutions of a system of non-linear equations. Several engineering reasoning and decision making activities are incorporated into this section and some are discussed below.

Materials for curve fitting are taken from Stoecker<sup>6</sup> and only two methods: linear and multi-variable regression, are discussed. Curve fitting or equation fitting is a mathematical tool for analysis of data whether it is from an experiment or a numerical simulation and interpretation of results. Three examples related to thermal systems are used to demonstrate the principle and practice of curve fitting.

The first example is taken from heat transfer class and consists of variation of thermal conductivity as a function of temperature. The data is first shown as a table without any headings and ask the students to make sense of the table. Once the students have responded, the same table with column headings but without the corresponding units are shown. The activity is intended to promote thinking skills in students as well as to stress the importance of units in engineering. Different forms of mathematical equations used in curve fitting are presented with their respective plots. Then, the next activity for students is to identify the most appropriate mathematical model or equation to represent the data in the most accurate manner. Here, the concept of deviation, least squares, and goodness of fit are discussed to provide meaningful curve fitting experience for students. Once the appropriate model is chosen, the process of curve fitting using both Microsoft Excel worksheet and Matlab script are presented in class.

The second example of curve fitting relates to thermodynamic properties such as enthalpy and entropy. The air standard table from Thermodynamic Textbook<sup>15</sup> is taken and polynomials of different orders (2<sup>nd</sup>, 3<sup>rd</sup> or 4<sup>th</sup> order) are used to represent air properties for different temperature intervals. Once the curve fit equations are obtained, the students are asked to generate the table properties and then decide the best polynomial



fit for the data. The purpose here is to provide students' experience of evaluating different curve fits mathematically using parameters such as  $R^2$ , standard deviation of errors and residuals to identify the best curve fit. The third example involves equation fitting of multi-variables as given in the text by Stoecker<sup>6</sup>. These curve fitting activities and examples are used so that students can do similar exercises while completing their computer projects as discussed later.

The next topic relates to the properties of fluids. Here, applications of curve fitting can be demonstrated through the use of both thermodynamic and transport properties. For example, the steam tables are an essential tool for providing properties of steam in the analysis of thermodynamic systems utilizing steam or water as working fluids. The students are asked to generate some properties of steam using X Steam Table for Matlab<sup>®</sup> from Excel Engineering<sup>16</sup> and compare the results with the standard steam table from the text<sup>15</sup>. X Steam Table is freely available in many formats including Excel, Matlab, Basic and LabView from the website of Excel Engineering. The following problem from the thermodynamic text<sup>15</sup> is given as an assignment to reinforce the concepts of both curve fitting and fluid properties.

*Air at 300 K and 200 kPa is heated at constant pressure to 600 K. Determine the change in internal energy using (a) air tables (b) constant specific heat (c) average specific heat (d) polynomial fit given in the text for specific heat and (e) curve fit in class for air tables. Compare the results and draw some conclusions.*

The third part deals with modeling of components and thermal systems. Only two types of thermal systems are considered: pipe and pumping systems and power systems. For each system, the process of identifying the system and its component, design variables (variables to be determined through analysis to satisfy the need/requirement), and parameters that are generally given or specified are presented. In addition, relevant engineering equations to model the components are discussed. It is to be pointed out to the students that the resulting equations for the system comprise a set of non-linear algebraic equations and numerical simulation of these systems involve solution of these non-linear equations. These steps are covered in details as they are necessary to implement successful simulation of thermal systems.

Pump and piping systems are much easier to deal with because they do not typically involve consideration of energy. A brief review of pipe flows including friction head loss, minor loss, and piping system characteristics are discussed followed by examples of piping systems from Stoecker<sup>6</sup>. For power generation systems, an example of stationary gas turbine system discussed in Stoecker<sup>6</sup> is used to demonstrate differences between pumping and power systems. For power systems, consideration of energy equation requires multi-variable regression equations for components such as compressors and turbines.

The last part deals with the solution methods for dealing with a set of non-linear algebraic equations. Successive substitution and Newton-Raphson methods are discussed

and both Excel and Matlab software packages are used to demonstrate the solutions of the modeling equations of pumping and power systems developed in the modeling section of the course.

### **Computer simulation of thermal systems**

The remainder of the course is devoted to computer simulation of thermal systems. A computer simulation of a simple gas turbine cycle using Matlab software is presented and discussed in class. Then, two computer projects are assigned to the students. The first project is based on the simulation of a pumping system given in the book, *Design and Simulation of Thermal Systems* by Suryanarayana et al.<sup>17</sup>. The problem consists of finding an operating point of a pumping system. The characteristic curve of the pump is given and a curve fitting is used to develop an equation of the pump curve. Then, the head loss of the piping system for a given pipe material, pipe size and length are computed and an operating point for the system is identified by computer simulation. For the present course, the students are asked to determine the effect of pipe diameter, pipe material, and pipe length on the operating point.

Project deliverables include a memo including the followings:

- Problem statement
- Polynomial curve fit of the pump characteristics
- Plot of pump curve with the curve fit
- Computer program and plots
- Results and discussions

The second project deals with the simulation of two gas turbine systems: one given in the textbook by Stoecker<sup>6</sup> and the other from the ASEE proceeding paper by Michael Sexton<sup>18</sup>. These two computer projects serve as platforms for students to demonstrate mathematical tools and skills on the simulation part of the course.

### **Group Design Project**

A design course will not be complete without a design project. Student design teams comprising four students are formed early in the semester and each group is assigned a design project on a specific thermal system. In the fall 2011 semester, the design project involves three thermal systems: a heat exchanger system, a cooling tower system and a piping system. These projects are intended to reinforce the concepts of the course as well as present students an opportunity to showcase their design, system thinking, engineering reasoning, and decision making skills. As George Morris mentions in his book, *Engineering: A decision Making process*<sup>7</sup>, the important part of each problem is not the exact answer (in most cases there is no exact answer), but rather the formulation of a solution. The project requires a submission of a technical report and an in-class presentation. In order to provide some guidance on the preparation of design report, two sample reports from American Society of Heating, Refrigeration, Air-

conditioning Engineers (ASHRAE) student design competitions were given to the students. These sample reports consists of detailed description of the design process followed by the student design team as well as life cycle cost analysis.

A detailed description of the pipe system is given below:

### *Pipe pressure drop project*

#### *Fluid*

1. *Water*
2. *Air*
3. *Natural gas*

*The objective of this project is to design a four-pipe pumping system to measure a pressure drop of the given fluid. The pipes are to be made of different materials and different diameters. The system is similar to the MEEN 3210 lab experiment "Pipe pressure drop". The pressure drop for each pipe should be the same, for example, pressure drop of 2 psi for water, for the same length of the pipe, e.g. a length of 10 ft. In order to achieve the same pressure drop, the design must include different pipe diameters and pipe materials. The design should include selection of a pump or a compressor to deliver the fluid to the system at a specified pressure drop. In addition, selection of appropriate flow meters and pressure gauges/sensors to be installed in the system for making measurements must be done. Flow meter options include rotameter (variable area flow meters), orifice plate meter, Venturi meter, or any other flow metering device. The pressure sensors may be Bourdon gauge, pressure sensors, manometers, etc. The project report must include economic analysis considering the life cycle cost.*

The project is similar to the lab completed by all students during another class, MEEN 3210 Measurements Lab. In order to complete the design, students are required to follow the steps below demonstrating design and critical thinking skills:

- Problem statement
- Design methodology
- Final design selection
- Design results and discussions
- Life Cycle Cost analysis

### **Assessment and results**

Course assessment consists of quizzes, exams, a design project and two computer simulation projects. In order to evaluate the students' learning regarding system thinking, engineering reasoning and decision making skills, some of the course evaluation instruments were modified. The first quiz of the course deals with assessing the system thinking skills. It consisted of three qualitative problems without any numerical computations. The ratings for the students' learning of system thinking are based on the

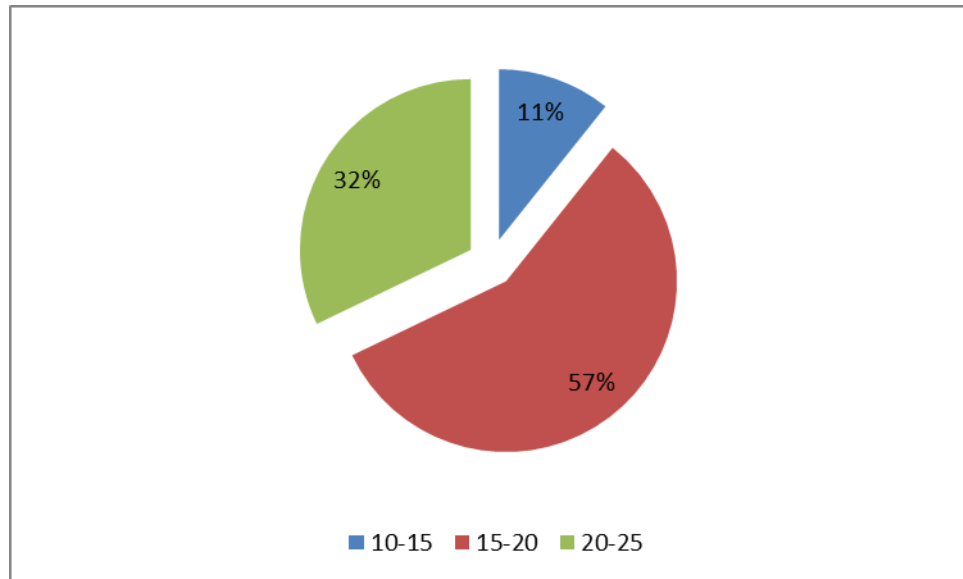
following scale with the total points for the quiz being 25 points. The rubric for assessing system thinking is given as Table 1.

- 10-15 points: poor
- 15-20 points: good
- 20-25 points: superior

Table 1 Rubric for assessing system thinking skills

Criteria	Rating		
	Poor	Good	Superior
System thinking	Does not demonstrate system thinking skills at all	Demonstrate some levels of system thinking skills	Demonstrate effective use of system thinking skills

The results of the assessments are given in Fig. 3 below. Out of 28 students, 16 students (57%) achieve good rating and 9 students (32%) achieve superior rating.



**Figure 3 Results of students' learning of system thinking skills**

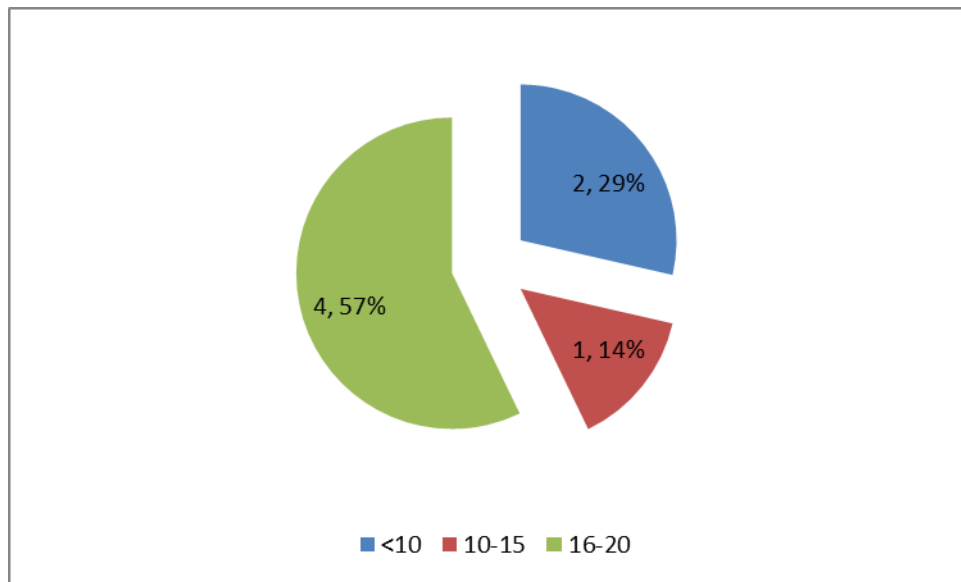
Engineering reasoning and decision making skills are assessed in various course evaluation instruments including exams, computer projects and a design project. One of the difficulties in using computer projects and a design project as assessment instruments is that these are group work rather than an individual student's work. As an example, the rating based on the design project worth 20 points is given below. The rubric for assessing engineering reasoning and decision making skills is given as Table 2.

< 10 points: poor  
 11-15 points: average  
 16-20 points: good

Table 2 Rubric for assessing engineering reasoning and decision making skills

Criteria	Rating		
	Poor	Average	Good
Engineering reasoning and decision making	Cannot demonstrate engineering reasoning or decision making skill in the project	Demonstrate some level of engineering reasoning and/or decision making skill in the project	Demonstrate both engineering reasoning and decision making skill in the project

Each group has 3 to 4 students and the results of the assessments are given in Fig. 4 below. Out of 7 teams of students, 4 achieve good rating and 9 students (32%) achieve superior rating. The current practice of using group work for assessing the engineering reasoning and decision making skills may not reflect individual achievement of the skills and future offering of the course will try to address the issue.



**Figure 4 Results of students' learning of engineering reasoning and decision making skills**

The effectiveness of integration of system and critical thinking skills to the course are assessed based on the end-of-semester student survey. It was done by adding one additional question to the online course evaluation. Early in the semester, many of the students showed reluctance to put efforts into development of the critical thinking skills discussed above as they are not used to think outside the box. However, as the semester progresses and more examples and activities are completed, many students realize the

importance of these skills in engineering design and problem solving processes. As a result, the students give an average of 4.2 rating on the integration of these skills as relevant to engineering design activities. The distribution of students' rating, with 5 being the highest and 1 being the lowest is given in Table 3. Out of 30 students in class, only 23 students completed the end-of-semester survey.

Table 3 Results of student's survey

Survey Question	Rating				
	1	2	3	4	5
Rate the usefulness of system thinking, engineering reasoning, and decision making skills.			9%	30%	61%

## Summary

Many senior engineering students do not have adequate preparation in applying design skills such as critical thinking, engineering reasoning, and decision making to successfully complete their design project. In this paper, the process of integrating system thinking, engineering reasoning, and decision making skills into Design of Thermal Systems course is described and the paper includes several class activities to promote and integrate these skills.

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