AC 2007-2156: DESIGN OF THERMAL SYSTEMS USING OPTIMIZATION AND METAHEURISTIC METHODS

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Abstract

The goal of an engineering education is the preparation of the engineers to solve industrial-type problems that are ill-structured, complex, and contain multiple constraints. One way to provide this type of problem solving environment in an academic environment is to use problem-based learning based on industry-supplied problems. A proposed course in thermal system design, for advanced undergraduates and graduate students, which uses a problem-based approach to teaching thermal system design is described. This proposed course uses operations research methods in a team-based problem solving environment that simulates an industrial setting.

Introduction

The purpose of an engineering education is to prepare the participating learners to solve industrial-type problems upon graduation. The types of problems that engineers face after graduation are ill-structured, complex, contain multiple (and sometimes conflicting) constraints, and have non-engineering limitations. Solving the typical classroom type word problems does not always work in terms of preparing the learner to solve these industrial-type problems[1].

To obtain an idea of what types of traits existed in industrial-type problems 106 practicing Professional Engineers, primarily civil engineers, in Missouri were interviewed[1]. Of these 106 interviews 78 were used to develop the following common traits of industrial problems:

1) Workplace problems are ill-structured.
2) Ill-structured problems include aggregates of well-structured problems.
3) Ill-structured problems have multiple, often conflicting goals.
4) Ill-structured problems are solved in many different ways.
5) Success is rarely measured by engineering standards.
6) Most constraints are non-engineering.
7) Problem solving knowledge is distributed among team members.
8) Most problems require extensive collaboration.
9) Engineers primarily rely on experiential knowledge.
10) Engineering problems often encounter unanticipated problems.
11) Engineers use multiple forms of problem representation.

During this interviewing process many of the practicing engineers recommended additional instruction for learners on client interaction, collaboration, communication, oral presentations, writing activities, and dealing with complexity and ambiguity[1].

One way to provide learners the opportunity to experience industrial-type problems in an academic environment is to use problem-based learning (PBL)[1]. In PBL the problem is provided to the learners then they must decide what knowledge needs to be acquired to solve the problem. This is typical of the industrial environment, a customer problem is provided and the practicing engineer (or engineers working in teams) determines what knowledge is required to generate an acceptable solution that addresses all of the customer's concerns, both those apparent and those not apparent to the customer.

The particular application of PBL in this paper is in the field of thermal science. Today's thermal scientist is using tools to help design thermal systems that were previously used only by operations researchers. In these applications the thermal engineers are attempting to develop a compromise of the many design variable and constraints to provide an optimal or near optimal solution. These design variables and constraints are formulated as a nonlinear programming problem, which is composed of an objective function, which is a function of the design variables. The objective function is maximized (or minimized) subject to the constraints[2]. Some of the various applications of optimization research in thermal systems design are as follows:

1) Genetic algorithms were used to determine the heat transfer characteristics in a turbulent boundary layer under a high heat flux environment where subcooled boiling exists[3]. This type of analysis would be used in the design of rocket nozzles and nuclear reactors.
2) Genetic algorithms were used to design green buildings which conserve resources, reduce waste, minimize life cycle costs, and create a healthy environment for the inhabitants[4].
3) Genetic algorithms and simulated annealing were used to generate heat transfer predictions for the design of compact heat exchangers[5].
4) Evolutionary algorithms were used to design thermal systems involving multiple objectives based on thermodynamics, economics, and environmental paremeters[6].

Genetic and evolutionary algorithms and simulated annealing are called metaheurestics[2].

A one-semester three-credit hour thermal system design course, for advanced undergraduates and graduate students, is proposed that uses a problem-based learning approach to teaching design using industrial problems. The Course Description section for the proposed course includes course objectives, outline of the weekly activities, and recommended textbooks. The Course Deliverables section contains the assessments for the course that mimic the types of deliverables that are found in industrial projects. The Course Implementation section describes how the course would be implemented. There is no data on the actual implementation of the course since this is only a proposed course at this stage.

Course Description

This course is focused on advanced undergraduates and graduates students who have successfully completed at least the standard three-semester series of undergraduate courses in thermal science (thermodynamics, fluid mechanics, and heat transfer).

Upon successful completion of this course the learner will be able to perform the following activities:

- Given thermal system customer design requirements determine the operational design variables including the probabilistic variation of the variables.
- Given a customer's design goal develop a work breakdown structure of the major tasks and time-sequence the tasks to meet expectations.
- Given the work breakdown structure carry out the design activities to meet customer expectations including:
    - Working effectively in a multi-disciplinary team.
    - Communicating project progress to the customer.
- Given the design of a thermal system apply state-of-the-art commercial software tools to generate viable solutions.
- Given a series of potential design parameters utilize optimization techniques in the design process.
- Given a completed design market the design to the customer and any potential customers.

To accomplish these objectives the week-by-week topics for the proposed one-semester, 15-week course are contained in Table 1.

Table 1 – Week-by-week course topics.

Week	Topics for the week
1	• Course introduction • Overview of the design projects • Stages of team development
2	• Team leadership • Project management overview • Quality Function Deployment • Design process
	Key deliverable: Project Team Definition Report
3	Preliminary Design Review Board for all teams
	Key deliverable: Preliminary Design Review Board material and Initial Project Plan
4	• Review of computational thermal science educational software • Summary of thermal system design
	Key deliverable: Team Project Status Report
5	• Innovation in design
	Key deliverable: Team Project Status Report and Team Self-Assessment Report
6	• Ethics in design • Economics in design
	Key deliverable: Team Project Status Report
7	• Probabilistic design overview • Basics of optimization
	Key deliverable: Team Project Status Report
8	• Basics of optimization • Metaheuristics

Week	Topics for the week
	Key deliverable: Team Project Status Report
9	• Metaheuristics
	Key deliverable: Team Project Status Report
10	Intermediate Design Review Board for all teams
	Key deliverable: Intermediate Design Review Board material and updated Project Plan (includes resources)
11	• Probabilistic design examples • Metaheuristics design examples
	Key deliverable: Team Project Status Report and Team Self-Assessment Report
12	• Requirements and format for the final design report • Additional topics to be determined by class needs
	Key deliverable: Team Project Status Report and draft of Final Design Review Board material
13	Final Design Review Board
	Key deliverable: Final Design Review Board material for all teams
14	Final Design Review Board
	Key deliverable: Final Design Report for all teams
15	Final Design Review Board
	Key deliverable: Marketing Plan, Team Self-Assessment Report, Final Project Plan, and Team Design Notebook

The resource material for the weekly topics is as follows:

1) Week 1 - Stages of team development from Blanchard[7], Tuckman[8,9], and Chapters 8 and 14 of Hersey[10].
2) Week 2 – Project management overview from PMBOK®[11], Quality Function Deployment from Chapter 6 of Ullman[12], design process from Chapter 4 of Ullman[12] and Chapters 1 and 2 from Suryanarayana[13].
3) Week 5 – Innovation in design from Kelley[14].
4) Week 6 – Ethics in design from Chapter 3 of Suryanarayana[13].
5) Week 7 – Economics in design from Chapter 7 of Bejan[15], Chapter 4 of Suryanarayana[13], and Chapter 8 of Blanchard[16].
6) Week 7 and beyond – Optimization and metaheurestics from Chapters 12 and 13 of Hillier and Lieberman[2].

The required textbooks for this course are as follows:

- Bejan, A, 1996. Thermal Design and Optimization. John Wiley & Sons, Hoboken, New Jersey.
- Blanchard, K., Carew, D., Parisi-Carew, E., 2000. The One-Minute Manager Builds High Performing Teams. William Morrow and Company, Inc. New York, New York.
- Kelley, T., 2001. The Art of Innovation: Lessons in Creativity from IDEO, America's Leading Design Firm. Doubleday, New York, New York.

These are in addition to the textbooks used in the undergraduate thermal science sequence. There is no recommendation on the course software since each vendor has a different cost structure and the university workstation capabilities would need to factor into the decision. Before the proposed course would be offered it would be necessary to make a software selection based on the individual university requirements.

The cornerstone of this proposed course is the course project. The projects are heat transfer based problems supplied by various industries that partner with the university. Although the project may incorporate other engineering and non-engineering disciplines it is primarily a heat transfer design problem. In addition to the course project the various sponsors also provide a practicing engineer who is knowledgeable in the problem and can act as a point contact for the learner team with the sponsor. The practicing engineer serves as a guide to provide data on and answer questions concerning the project. The projects are based on problems that tend to be ill-structured and initially poorly defined and involve several disciplines (not all are engineering-related) and have a number of possibly conflicting constraints (some of which are non-engineering). There may not be an optimal design that satisfies all the problem objectives but there may be a number of designs that are near optimal.

Course Deliverables

Table 1 lists the various deliverable for this proposed course. These are typical of the types of deliverables for an industrial project and range from the documentation of project plans to communication with the customer to documentation of the project analyses and conclusions. This section contains a brief description of the various course deliverables, with Table 2 containing the percent of the final grade assigned to each assignment or group of assignments.

Table 2 – Grading distribution.

Team Assignment	Percent of final grade
Project Team Definition Report, Team Project Status Reports (7 total), and Team Self-Assessment Reports (2)	10
Preliminary Design Review Board	5
Initial Project Plan	5
Team Design Notebook	20
Intermediate Design Review Board	15
Final Design Review Board *various components of the Final Design Review Board are as follows (percent of final grade in parentheses):* • *Final Design Report (20 percent)* • *Design Review Board Presentation (15 percent)* • *Marketing Plan* • *Final Team Self-Assessment* • *Final Project Plan* The Marketing Plan, Final Team Self-Assessment, and Final Project Plan account for 5 percent of the final grade.	40
Class Participation	5

The Project Team Definition Report is submitted during Week 2 of the course. The following items need to be included in this report:

- Team members' names and email addresses.
- Team project definition.
- Initial thoughts on the scope of the project.
- Initial concerns with respect to the project.
- Initial list of work activities and Work Breakdown Structure.
- Definition of tentative team meeting times and locations.
- Assignment of team roles (roles may rotate if the team desires, in which case the rotation system must be provided).

The seven Team project Status Reports are filed throughout the semester. The format for the Team Project Status Report is as follows:

- Statement of the work period (time from last Project Status report (or start of the semester)).
- Summary of the major accomplishments during the work period.
- Summary of problems during the work period.
- Summary of what has been learned over the work period.
- Progress against original schedule and reasons for any deviations from the original schedule.
- Number of meetings held (date, time, attendees) and summary of meeting topics.
- Number of man-hours worked per team member since the last Project Status Report.

Two Team Self-Assessment Reports are submitted during the semester and along with the final Team Self-Assessment Report comprises part of the final project deliverable. The purpose of these is to determine how the team is operating and progressing through the stages of team performance. The various items to be addressed by each team member for the two Team Self-Assessment Reports are the following (no more than one page per team member):

- Explain how the team is functioning.
- What are the major team weaknesses? Why?
- What are the major team strengths? Why?
- How would you rate the team on a scale of 0 to 100 (with 100 being the highest possible score in terms of team performance)?
- What stage of team development is in the team in? Why? What leadership strategies is the team leader using to move the team to the next stage of team development?

The requirements for the Final Team Self-Assessment are as follows:

- Explain how the team functioned.
- What are the major team weaknesses? Why?
- What are the major team strengths? Why?

- How would you rate the team performance on a scale of 0 to 100 (with 100 being the highest possible score in terms of team performance)? Why?
- What have you learned about the dynamics of teams?
- Based on your lessons learned from this course what will you do differently on your next work team? Why?

This Final Team Self-Assessment is intended to make the learner reflect back on the semester's activities and develop some lessons learned for the next project team on which the learners are involved.

There are three Design Review Boards (DRB) scheduled throughout the semester. The three DRBs consist of both an oral presentation and a written report. The oral DRB presentations are made in front of the class and a review board consisting of a panel of experts (in this case a few randomly selected learners from the course, instructor, and experienced engineer) who review and provide comments on the design at various stages during the semester. The Preliminary DRB consists of a 10-minute presentation and a written preliminary design report that address the following:

- Adequately defined the customer problem.
- Translated the customer's current and future needs into the design process.
- Adequately defined the tasks necessary to complete the project.
- Generated a project plan.

The Intermediate DRB occurs in Week 10 of the semester and consists of a 20-minute presentation by the learner team and a written design report that addresses the following:

- Adequately defined the customer problem.
- Translated the customer's current and future needs into the design process.
- Generated an up-to-date project plan including tasks completed to date.
- Addressed issues raised during the Preliminary DRB.
- Adequately addressing various stages of the design process.
- Technical analyses and activities (including simulations, prototypes, etc) support the conclusions or viability of options to date.

The Final DRB is the culmination of the semester's team design project. The Final DRB and Final Design Report will include not only the design recommendations supported by your technical analyses but also a Marketing Plan, Final Team Self-Assessment, and Final Project Plan. The requirements for the Final DRB are as follows (60-minute time limit per team (45 minutes for presentation then15 minutes for questions) with all team members participating):

- Define the customer problem. Verify that it addresses the root cause of the problem.
- Demonstrate that all the steps in the design process have been followed.
- Describe the highlights and struggles with each of the design steps.
- Describe the solution to the customer's design problem and demonstrate how the design meets the customer's needs (including prototypes or simulations).

- Describe any key learnings from this process (technical and non-technical).
- Define any future work.

There are two project plans required. These are the Initial Project Plan during Week 3 and the Final Project Plan, which is submitted during the last week of the course. The purpose of the Initial Project Plan is to develop the work plan that will allow the project to be completed on time and in budget. The Initial Project Plan needs to address the following required items:

- Definition of the major project tasks.
- Provide an estimate of the number of hours it will take to complete each major task.
- Defining a Gantt-type chart that shows when the major tasks will be completed.
- Defining the critical path through all the tasks.
- Identification of major deliverables and key decision points.

The requirements for the Final Project Plan are as follows:

- Define the final project work plan.
- Compare this to the Initial Project Work Plan and explain the deviations.
- Provide the final Gantt-type chart showing the final time line.
- Provide an estimate of the hours spend on each of the work tasks in the final project plan.

The Team Design Notebook contains the results of all the work the team performed to solve the customer's problem, even if the work was for an alternative that did not prove viable. This would include sufficient detail such that another design team could repeat the work. The following items must be included in the Team Design Notebook:

- Table of Contents showing all the steps of the design process.
- Summary of results for each phase of the design process.
- Details of the analyses necessary to support the design decisions.
- Indication of who on the team performed each analysis.
- All project plans (baseline and all updates plus supporting documentation).
- Link between the analyses and the conclusions in the Final DRB.
- List of all references used in the analyses.
- Summary and conclusions of analyses.
- Recommendations for future work.
- Meeting minutes, including Action Items, for all team meetings.
- References used during the course of the analyses.

The requirements for the Final Design Report are as follows:

- Follow the format of the Design Report provided in class.
- Define the customer problem. Verify that it addresses the root cause of the problem.
- Document the steps of the design process and demonstrate that they have been adequately followed.
- Describe the various alternatives examined and why they were or were not selected.

- Link the results in the Final Design Report to the sections in the Team Design Notebook and the Final DRB that support the final conclusions.
- Provide a list of which learner had the lead on which sections of the Final Design Report.
- List all references supporting the final design.

The requirements for the Marketing Plan are as follows:

- Define the market for the final design.
- Provide a list of the final designs advantages over what is currently available in the marketplace.

Course Implementation

This is a one-semester three-credit hour course intended for learners with a thermal science background. Although it is intended as a graduate course it could be offered to undergraduates but with a strong background in thermal science. Some of the other entry skills for this course are as follows:

- Programming skills.
- General project management skills.
- Working in teams and resolving team conflict skills.
- Willingness to try something different.

The lectures identified in Table 1 are meant to support the project work, which is the focus of the course. The topics to be covered are subject to change based on the needs of the various learner project teams. The lectures are provided by the lead instructor but may also be provided by experienced engineers from the companies sponsoring the projects or from subject matter experts.

The focus of this course is the project as a motivator for learning. The learner teams are expected to follow sound project management techniques[11] in carrying out the projects. This includes having frequent team meetings and remaining in contact with the engineer from the company sponsoring the project, both to provide project progress but also as a resource person to assist the learner teams in identifying the root causes of the problem as well as identifying areas of concern outside the thermal science realm. Ultimately the learner teams are responsible for project team performance.

Example Application of Metaheuristics for Heat Transfer Application

Several examples of the use of operations research tools in the solution of thermal science problems were listed previously. One of the examples that is similar to the application in this proposed course is the use of metaheurestics in the design of green buildings[4]. This particular application uses metaheurestics in conjunction with a thermal system design computer code.

The optimal design of green buildings requires that a number of trade-offs be made between various variables, such as construction materials, construction costs, life cycle operating costs (including the local electricity costs), building size and orientation, etc. Two objective functions were developed for the life cycle cost (including construction and building operation) and an environmental impact function as a function of the various design variables. The constraints on the system include various limitations on building materials (such as window sizes and insulation ratings), which are both integers and continuous variables. A genetic algorithm, which is classified as a metaheuristic[2], is coupled with a building design computer code to develop an optimal or near optimal building design[4]. This is the same type of activity that will be used in this course's design project.

Conclusions

A problem-based thermal science course is proposed for providing learners an opportunity to encounter the types of problems typically found in industry. Industrial problems, including those used in this proposed course, are typically: ill-structured; have conflicting and non-engineering goals and constraints; require project teams to arrive at a solution; have multiple solution strategies; require communication skills in dealing with both engineers and non-engineers; and typically encounter unanticipated problems[1]. The industrial problems used in this course are supplied by a cooperating industrial sponsor. The projects are solved in a team environment using standard project management skills. The learner teams use industrial-type methods for reporting project progress to the customer, justifying the design to a design review board, and documenting the results of the design and the design process. This approach provides the learners the opportunity to experience many of the common traits of industrial problems[1] thereby providing the learners both technical and non-technical skills that are needed to succeed in industry.

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