TEEHOUSE: Thermal Environmental Engineering Design and Cost Software for a Building

Craig W. Somerton, Laura Genik, Wayne Thelen, Dan Lewis, and Scott Strawn

Michigan State University/University of Portland/Michigan State University

Introduction

Computer software has been developed that performs the simple calculations associated with the design and cost analysis for the heating and air conditioning systems for a building. TEEHouse (**T**hermal **E**nvironmental **E**ngineering **House**) is an interactive DOS program that allows for the optimization of insulation type and thickness, furnace type, and air conditioner type in thermal environmental engineering design. The software is used in senior level thermal design classes at the University of Portland and Michigan State University to teach the basic principles of HVAC design within the context of a realistic problem. The program utilizes weather data, such as daily temperature, relative humidity, wind velocity, and solar condition, for ten different U.S. cities that are used in the heating and cooling load calculations performed by the program. The analysis can be performed for average or extreme temperature conditions for each location. Heating and cooling loads, as well as the design/costing analysis, can be performed on a daily basis or an annual basis. The economic analysis allows for an appropriate selection of insulation type, insulation thickness, furnace type, and air conditioner type to be explored by the students, including the interaction among these selections.

This paper provides a detailed description of the operation of the program, including details of the heating and cooling load calculations and economic analysis. Three different design problem statements are provided that deal with the thermal design of a house, a refrigerated warehouse, and a power plant building. Results of these design studies are provided to demonstrate the utility of the software. Student feedback is provided to assess the program and design experience. Finally, recommendations concerning the use of the program and the design projects are provided.

TEEHouse Program

The software TEEHOUS.EXE is an interactive DOS program for the design and cost analysis of the heating and air conditioning systems for a building. It allows for the optimization of insulation type and thickness, furnace type, and air conditioner type. The program may be run from Windows by clicking on the program icon labeled TEEHOUS.

The initial menu requests geographic and other information concerning the building. The building may be specified as either a one story or two story structure. The air change per hour (ACH) is also specified to calculate the infiltration heat transfer. Two design studies are possible: single day analysis for which the user will provide the specific day to carry out the calculations and an annual year analysis for which the heat transfer calculations are carried out on a half day basis for the entire year. The single day analysis will consider only a heating or cooling optimization (depending of the day chosen) while the annual year analysis will perform both a cooling and heating optimization. If the annual year analysis is chosen, an inside temperature for both heating and cooling must be provided by the user. Economic information is then requested, including natural gas costs, electricity cost, interest rate, and building lifetime (the later two for the time value of money calculation). Finally, the insulation, furnace, and air conditioning choices are inputted. The format of the menus is found in Fig. 1.

The insulation board is available in 50 mm, 75 mm, 100 mm, and 125 mm thicknesses. To develop thicknesses greater than 125 mm, one or two additional layers of board are required. The program allows for a maximum of five layers of insulation board. Three options are provided for the type of insulation. Type A insulation costs 5 cents per square meter of area for each millimeter of thickness and has a thermal conductivity of 0.04 W/(m K). Type B insulation costs 6 cents per square meter of area for each millimeter of thickness and has a thermal conductivity of 0.03 W/(m K). Choosing Type C insulation allows the user to specify both the cost and thermal conductivity of the insulation. Installation costs for the board are $2.50 per square meter for the first layer and $1.50 per square meter for each subsequent layer. There are two furnace choices available to the user. One furnace has an efficiency of 80% while the other has an efficiency of 90%. The capital cost of the furnace equipment is given by the following relationships.

80% efficiency furnace: Cost(in $) = 450 + 4 x Load(in kW)
90% efficiency furnace: Cost(in $) = 900 + 5 x Load(in kW)

The user may choose an air conditioner with COP of 2 or 3. The capital cost of the air conditioning equipment is given by the following relationships.

AC with COP of 2: Cost(in $) = 600 x Load(in kW)
AC with COP of 3: Cost(in $) = 800 x Load(in kW)

With all of the required input provided, calculations are then performed and results are displayed to the screen. As shown in Fig. 1, results include both a summary of the heat transfer calculations and the economic analysis. Results are also written in appending form to the file TEEHOUS.TXT, which will be created in the default directory. The user is then prompted for another program run where the furnace or air conditioner choices may be changed or the roof and/or wall configuration may be changed. If both the roof and wall configuration are to be changed, then the user should respond no to the questions concerning changing the roof or wall configuration.

Heat transfer calculations are performed assuming that only the insulation contributes to the thermal resistance of the walls or roof. Also sunlight is assumed to fall only on the roof. If the annual year analysis is chosen, the normal high temperature is used for the daytime calculations and the normal low temperature is used for the nighttime calculations. The solar flux is calculated as the average solar insolation between 9:00 am and 4:00 pm local time and is used only for the day time calculations. The cost presented in the output is the present value cost of the system

Figure 1. Operation of TEEHouse

```
******************************************************
*      TEEHOUS: Thermal Environmental Engineering     *
*                      HOUSe                          *
*                   Version 2.2                       *
*      Copyright 2000 Craig W. Somerton               *
*                  Scott S. Strawn                    *
*                  Wayne Thelen                       *
*                  Dan Lewis                          *
*                  Laura J. Genik                     *
******************************************************

CHOOSE DESIGN STUDY LOCATION:
   1. NEW YORK CITY                    6. MIAMI
   2. DETROIT                          7. SALT LAKE CITY
   3. CHICAGO                          8. SEATTLE
   4. LOS ANGELES                      9. PHOENIX
   5. INTERNATIONAL FALLS             10. PORTLAND
INPUT A CHOICE (1-10):

INPUT HOUSE CONFIGURATION:
 LIVING SPACE AREA (m^2):
 NUMBER OF STORIES (1 OR 2):
 INPUT HOUSE AIR CHANGE PER HOUR:

CHOOSE DESIGN STUDY:
   1. SINGLE DAY ANALYSIS
   2. ANNUAL HEATING AND AIR CONDITIONING
INPUT A CHOICE (1-2):

INPUT THE DESIRED INTERIOR AIR TEMPERATURE FOR
AIR CONDITIONING (DEGREES K):

INPUT THE DESIRED INTERIOR AIR TEMPERATURE FOR
HEATING (DEGREES K):

CHOOSE A CONDITION FOR THE EXTERIOR HEAT TRANSFER
1. NATURAL CONVECTION
2. FORCED CONVECTION USING AVERAGE MONTHLY WIND VELOCITY
3. FORCED CONVECTION USING MAXIMUM MONTHLY WIND VELOCITY
4. FORCED CONVECTION WITH USER PROVIDED WIND VELOCITY
PLEASE ENTER A SELECTION (1-4):


INPUT A WIND VELOCITY (M/S):
```

Figure 1. Operation of TEEHouse (continued)

CHOOSE A CONDITION FOR THE OCCUPANCY LOAD
1. NO OCCUPANCY LOAD
2. USER SPECIFIES OCCUPANCY LOAD
3. STANDARD OCCUPANCY LOAD FOR LIVING SPACE
PLEASE ENTER A SELECTION (1-3):

INPUT THE NUMBER OF ACTIVE OCCUPANTS:

INPUT THE NUMBER OF INACTIVE OCCUPANTS:

INPUT ECONOMIC/COST INFORMATION:
INPUT NATURAL GAS COST ($/kW*hr):
INPUT ELECTRICITY COST ($/kW*hr):
INPUT ANNUAL INTEREST RATE (%):
INPUT BUILDING LIFETIME (yrs):

INPUT ROOF DESIGN:
INPUT NUMBER OF INSULATION BOARDS (MAX 5):

SELECT TYPE OF INSULATION FOR LAYER 1:
1. TYPE A, K=0.04 W/m*K, COST=$0.05
2. TYPE B, K=0.03 W/m*K, COST=$0.06
3. TYPE C, USER SPECIFIED K AND $
INPUT A CHOICE (1-3):

SELECT INSULATION THICKNESS FOR LAYER 1:
1. 50 mm
2. 75 mm
3. 100 mm
4. 125 mm
INPUT A CHOICE (1-4):

INPUT WALL DESIGN:
INPUT NUMBER OF INSULATION BOARDS (MAX 5):

SELECT TYPE OF INSULATION FOR LAYER 1:
1. TYPE A, K=0.04 W/M K, COST=$0.05
2. TYPE B, K=0.03 W/M K, COST=$0.06
3. TYPE C, USER SPECIFIED K AND $
INPUT A CHOICE (1-3):

SELECT INSULATION THICKNESS FOR LAYER 1:
1. 50 mm
2. 75 mm
3. 100 mm
4. 125 mm
INPUT A CHOICE (1-4):

Figure 1. Operation of TEEHouse (continued)

```
INPUT FURNACE TYPE:
   1. TYPE 1: EFF=80%, COST=$500 AT 10 kW
   2. TYPE 2: EFF=90%, COST=$970 AT 10 kW
INPUT A CHOICE (1 OR 2):

SELECT AN AIR CONDITIONER (1-4):
   1. TYPE 1:  COP=2, COST=$600/kW
   2. TYPE 2:  COP=3, COST=$800/kW
INPUT A CHOICE (1-2):

********* HEAT TRANSFER ANALYSIS ***********

AVERAGE DAILY SOLAR FLUX:                          172.7 W/m^2
AVERAGE DAILY TEMPERATURE:                               289.6 K
AVERAGE NIGHTLY TEMPERATURE:                             281.7 K
COOLING LOAD AVERAGE ROOF HEAT FLOW:                    7066.3 W
COOLING LOAD AVERAGE WALL HEAT FLOW:                    5746.6 W
COOLING LOAD AVERAGE INFILTRATION HEAT FLOW:             700.4 W
NUMBER OF COOLING DAYS:                                     47.0
HEATING LOAD AVERAGE ROOF HEAT FLOW:                    5212.7 W
HEATING LOAD AVERAGE WALL HEAT FLOW:                    2030.8 W
HEATING LOAD AVERAGE INFILTRATION HEAT FLOW:            5653.8 W
NUMBER OF HEATING DAYS:                                    233.5

Pause - Please enter a blank line (to continue) or a DOS command.

********** COST DATA ************

NATURAL GAS COSTS:            $ 16375.12
FURNACE COSTS:                $   454.00
ELECTRICITY COSTS:            $  2888.39
AIR CONDITIONER COSTS:        $   604.69
ROOF INSTALLATION COSTS:      $  1995.00
ROOF MATERIAL COSTS:          $  1995.00
ROOF TOTAL COSTS:             $  3990.00
WALL INSTALLATION COSTS:      $   597.68
WALL MATERIAL COSTS:          $   597.68
WALL TOTAL COSTS:             $  1195.35
INSTALLATION COSTS:           $  2592.68
MATERIALS COSTS:              $  2592.68
TOTAL COSTS:                  $ 25507.55

DO YOU WANT TO TRY ANOTHER AIR CONDITIONER?

DO YOU WANT TO TRY ANOTHER FURNACE?

DO YOU WANT TO CHANGE THE WALL CONFIGURATION?

DO YOU WANT TO CHANGE THE ROOF CONFIGURATION?

DO YOU WANT TO CHANGE BOTH THE ROOF/WALL CONFIG.?

DO YOU WANT TO CHANGE OTHER INPUT DATA?
```

utilizing the appropriate time value of money factor to convert the annual fuel and electricity costs into present value costs.

Thermal Design Projects

Over the years, three different thermal design project statements have been developed and utilized: thermal design of a house, thermal design of a building, thermal design of a refrigerated warehouse. Summary statements for these projects are given in Table 1. Normally student teams of two are assigned, and it proves very convenient to ask for two separate design studies. The team of two students can consider a one story building and a two story building located in the same city as their two studies or either a one story or a two story building located in two different cities for their two studies. This allows the students to work independently on the project, once they agree upon their design parameters. However, students are required to perform a comparative analysis of their design solutions. All three projects have two basic components: an optimization study for which the team decides on the best combination of furnace, air conditioner, insulation thickness and insulation type, and a robustness study for which the team analyzes their three best designs for different conditions of interest rate, ACH, fuel price, etc.

For the optimization study the following parameter values are set.

ACH: 0.5
Interest Rate: 11%
Building Life: 25 years
Natural Gas Price: 2.5 cents per kilowatt-hour
Electricity Price: 4.5 cents per kilowatt-hour

It is suggested that the students perform the optimization by first choosing an insulation type and then maintaining the roof and wall at the same insulation thickness. Then starting at the smallest possible thickness, march out by increasing the thickness. At each thickness the students should have the program calculate the cost for all four combinations of furnace and air conditioner types. Once the combination of thickness, furnace type, and air conditioner type that yields the lowest cost for the chosen insulation is identified, the students repeat the process with the other insulation type. At this point the lowest cost system with the roof and wall at the same configuration will have been identified. The students are then asked to explore minimizing the cost further by allowing the wall and roof configurations to be different. They are urged to view the wall and roof heat transfer results as a guide to this exploration. Every year it amazes the authors that this will be the student's first experience in performing an optimization through a parametric study. Hence, without these directions, most of the students would be totally lost. As part of the optimization study the students are required to produce graphs of cost versus insulation thickness for the case of the two different furnaces, two different air conditioners, and two different insulation types. An example of such a graph is shown in Fig. 2. These graphs allow the students to build some intuition concerning the physical processes at work. They are also required to produce a bar graph showing the various cost components (see Fig. 3).

Table 1. Project Statements

Climate Control Design of an Office Building

The Rhino Thermal Engineering Company has recently received a contract to provide a northeastern (or northwestern) college with a system design and optimization for a steam power system. The college has decided to satisfy its power requirements by building a power plant. Though the electric load requirements are not that great, it has been decided to oversize the power plant and then sell electricity on the grid so as to raise money for the university. A second contract has been awarded to perform the HVAC design associated with the power plant offices. Several principals of the company, Dr. Craig W. Somerton, Dr. Laura J. Genik, Mr. Scott Strawn, Mr. Dan Lewis, and Mr. Wayne Thelen, have developed a computer program that can be used to optimize the insulation, air conditioner, and furnace choices for the heating and cooling of a building. To complete the contract a design team of two or three students has been assigned for the optimization study.

Climate Control Design of a House

The Rhino Thermal Engineering Company has contracted to provide technical support on HVAC for the builder of a residential dwelling subdivision. Several principals of the company, Dr. Craig W. Somerton, Mr. Scott Strawn, Mr. Dan Lewis, Mr. Wayne Thelen, and Dr. Laura Genik, have developed a computer program that can be used to optimize the insulation, air conditioner, and furnace choices for the heating and cooling of a house. To complete the contract a design team of two or three students have been assigned for the optimization study.

Design of a Refrigerated Warehouse

The Rhino Thermal Engineering Company has contracted to provide technical support on HVAC for a food company that is building a refrigerated warehouse of dimensions 50 ft x 50 ft x 20 ft high. The warehouse temperature is -18°. Several principals of the company, Dr. Craig W. Somerton, Mr. Scott Strawn, Mr. Dan Lewis, Mr. Wayne Thelen, and Dr. Laura Genik, have developed a computer program that can be used to optimize the insulation, air conditioner, and furnace choices for the heating and cooling of a house. To complete the contract a design team of two or three students have been assigned for the optimization study.

Figure 2. System Cost versus Insulation Thickness for Two Different Furnaces

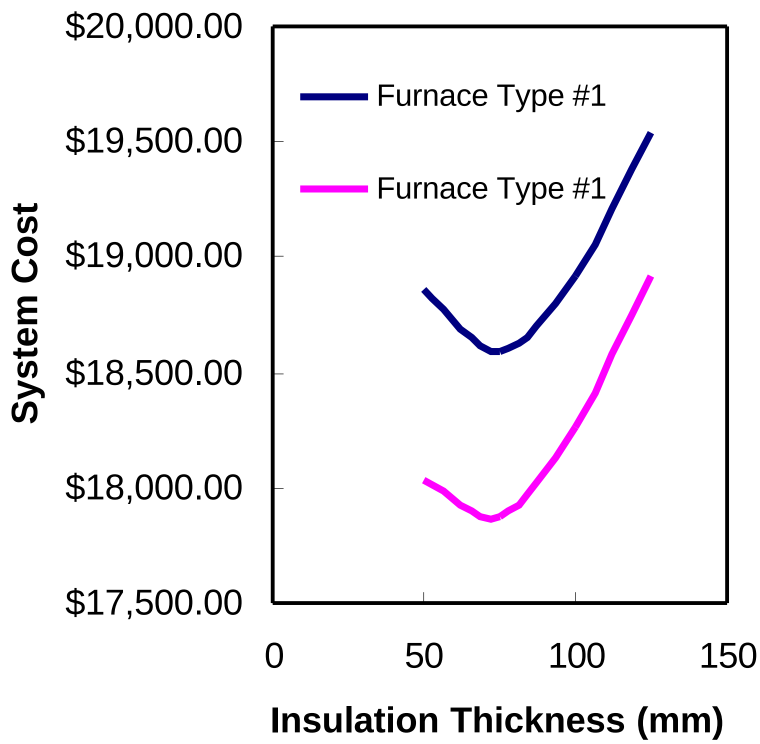
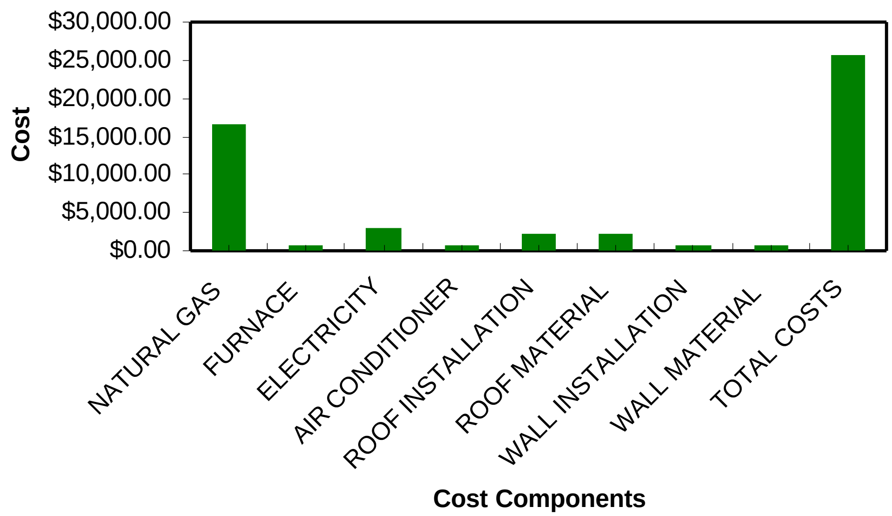


Figure 3. System Cost Breakdown



For the robustness study the students are asked to consider how the optimal design and two competing designs are affected as the ACH, interest rate, and building life are allowed to vary from the base conditions set for the optimization study. Figure 4 shows the results for such a study with a varying interest rate. Nearly all of the students are puzzled by the decrease in the cost with increasing interest rate. This is due to the fact that the student's own experiences with interest rate have primarily been with monthly car payments, or an annual cost approach. The cost they are using is a present cost, and so the difference between these two types of money must be explained further. The two other parts of the robustness study involve investigating prices that will make two designs comparable in cost. The team is asked to determine the gas price that makes both furnaces optimal choices for the optimal base case design and the insulation price that makes both insulations optimal choices. Figure 5 shows typical results of the natural gas price analysis.

The students are to submit their design studies in the form of a technical memo that is graded by the instructor using the form shown in Fig. 6. The use of such a form can shorten grading time considerably, especially when grading some thirty odd memos. The grading sheet is provided to the students in the project write-up, so that there are no surprises.

Student Evaluation

The students were surveyed concerning their experience with TEEHouse and the project. The survey form is shown in Figure 7. Of the 83 students surveyed, 50 responded. The student response was exceptionally positive for the ease of use and distribution of the program. The students found the running of multiple cases to strongly improve their understanding of the thermal design and analysis of building operations as well as the impact of several variables on the overall cost of the HVAC system for a building. Several students suggested a change in the interface of the program where multiple loops could be run without re-entering the initial set-up data. This is a feature that the program designers are aware of and will incorporate in future versions. Surprisingly, students were not put off by the DOS interface. Few students suggested changing the interface to "pop-up" menus or a spreadsheet. One student suggested re-writing the code in either C++ or MATLAB so that the students could have the source code to manipulate. The language has no bearing on the students use of the source code as the instructors chose to supply only the executable program. Further suggestions for improving the program include: adding more cities, alerting the user to erroneous entries, and formatting the output to be easily read by Excel or similar programs. With regards to improving the assignment, students suggested analyzing changes in the internal temperature of the building and its impact on overall cost, requiring a hand calculation of the analysis, and allowing more time to do background research on thermal design of buildings. One student commented that the entire project seemed like number crunching and did not feel that it provided additional understanding to the thermal design and analysis of the building. Another student felt that specific nature of the output requirements did not allow them the flexibility to present results in their own fashion. Still, as stated previously, overall the response was very positive.

Conclusions and Recommendations

A very straight forward computer program, TEEHouse, has been used in the instruction of thermal environmental engineering. Though it involves simple models, the program provides students with the opportunity to explore realistic problems through optimization studies and

Figure 4. System Cost with Varying Interest Rate

Case 1: Furnace Type #2, Air Conditioner Type #2
Wall with 75 mm of Insulation Type #2
Roof with 75 mm of Insulation Type #2
Case 2: Furnace Type #2, Air Conditioner Type #2
Wall with 50 mm of Insulation Type #2
Roof with 50 mm of Insulation Type #2
Case 3: Furnace Type #2, Air Conditioner Type #2
Wall with 75 mm of Insulation Type #1
Roof with 75 mm of Insulation Type #2

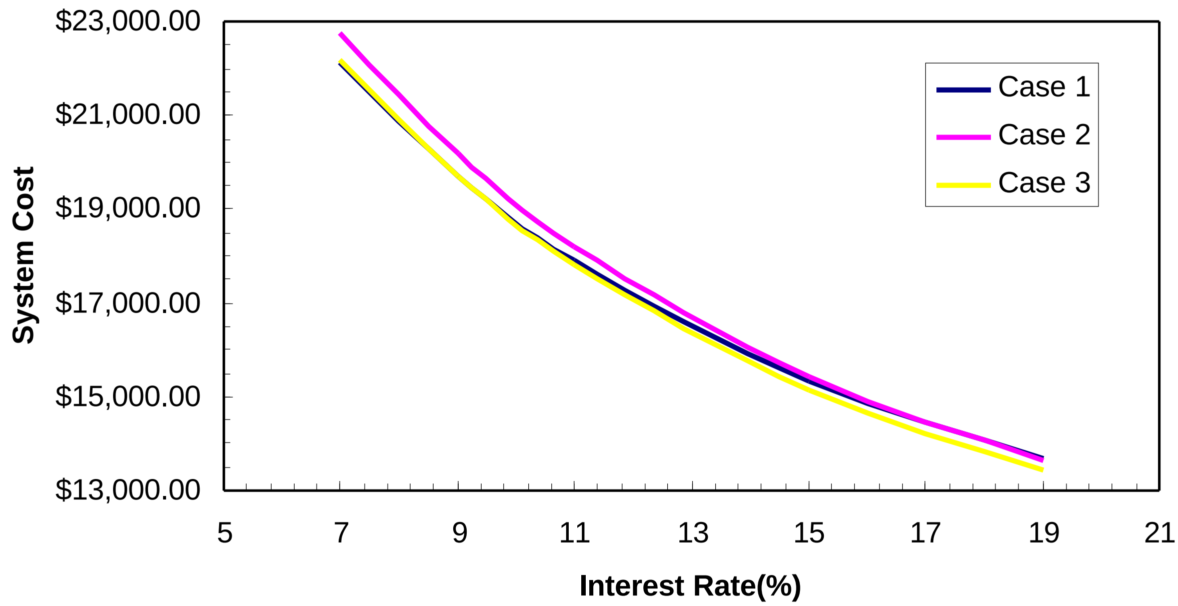


Figure 5. System Cost for Varying Natural Gas Price for both Furnace Types

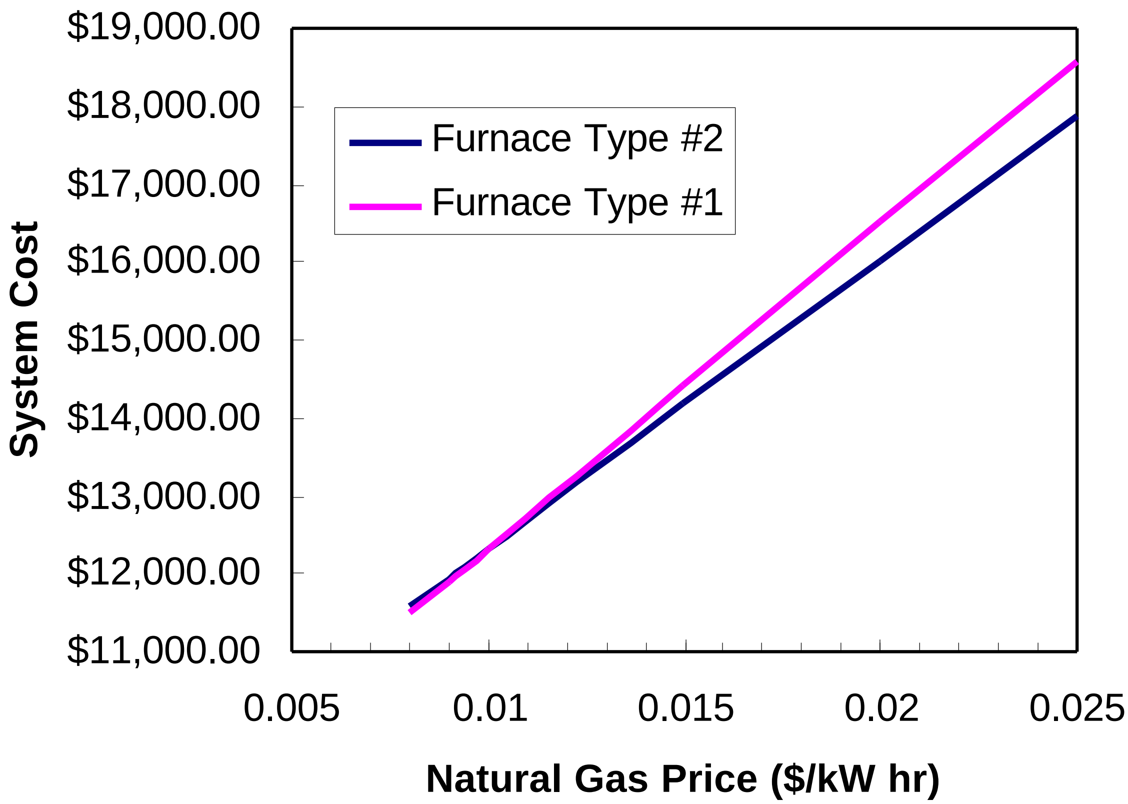


Figure 6. Project Grading Form

Student Name: ____

Student Name: ____

Topic	**Building #1**	**Building #2**	**Total**
Base Condition Design			**60**
Optimization			**20**
Insulation Thickness Graph for different furnaces			**10**
Insulation Thickness Graph for different air conditioners			**10**
Insulation Thickness Graph for different insulations			**10**
Comparing the different costs for the optimization			**5**
Different Wall/Roof Configurations			**5**
Robustness Study			**30**
ACH			**6**
Interest Rate			**6**
Building Lifetime			**6**
Gas Cost/Furnace Choice			**6**
Insulation Cost			**6**
Final Recommendation			**10**
TOTAL			**100**

Figure 7. Student Survey Form

Evaluation of Project 3 Program
Thermal Environmental Engineering House (TEEHOUSE.EXE)

1. Please comment on the ease or difficulty in the use the program and the method in which it was delivered to you (via web, disk, email)

2. Did the project assignment aid in improving your understanding of building design and optimization? Specifically how the insulation, air conditioner, and furnace choices for the heating and cooling of a building may be determined.

3. In running multiple cases of one system, were you able to better understand the operation of the system as a whole as opposed to the traditional manner of analyzing a building (hand calculation).

4. Any suggestions for improvement in the program and/or assignment?

parametric analysis. Students found the ease of use of the program and ability to determine the impact of several variables on the cost and function of heating and cooling of buildings greatly enhanced their understanding of these concepts. Both the program and user's guide are available for access and download at the Thermal Engineering Computer Aided Design (TECAD) homepage in the Department of Mechanical Engineering at Michigan State University. The URL address is

http://www.egr.msu.edu/~somerton/TECAD.

The program has been used with success in teaching senior level elective courses in thermal design at both Michigan State University and the University of Portland.

CRAIG W. SOMERTON
Craig W. Somerton is an Associate Professor of Mechanical Engineering at Michigan State University. He teaches in the area of thermal engineering including thermodynamics, heat transfer, and thermal design. Dr. Somerton has research interests in computer design of thermal systems, transport phenomena in porous media, and application of continuous quality improvement principles to engineering education. He received his B.S. in 1976, his M.S. in 1979, and his Ph.D. in 1982, all in engineering from UCLA.

LAURA J. GENIK
Laura J. Genik is an Assistant Professor of Mechanical Engineering at the University of Portland. She teaches in the area of thermal engineering, including thermodynamics, heat transfer, and thermal system design. Dr. Genik has research interests in transport phenomena in porous media, inverse problems and parameter estimation in heat transfer processes, and computer design of thermal systems. She received her B.S. in 1991, her M.S. in 1994, and her Ph.D. in 1998, all in mechanical engineering from Michigan State University.