The Educational Value of Modelling Complex Thermodynamic Systems with System Dynamics Software

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Abstract

The solution of problems involving complex thermodynamic systems often occupies much of a students' time and can be a distraction from them developing a clear understanding of system components, interaction of subsystems, modelling simplifications and assumptions, and design optimization. Refocusing students on the fundamental concepts of thermal systems design and analysis is possible with the introduction of system modelling software that carries some of the load of repetitive calculation required for complex systems. Models of thermodynamic systems encountered in an advanced undergraduate thermodynamics course were developed by students (some provided to students) to solve homework problems of complex steam power plants, internal combustion engines, gas turbine power plants, refrigeration, and building energy systems. Computer modelling systems used included two commercial modelling programs, an open source program, and systems developed by the authors. Use of the modelling software forced students to setup problems in the same way as if solved on paper but allowed them to identify common components and processes that could be modeled by common blocks and used in multiple thermal systems. One example presented is a simple process block that gives the state for any location in a converging/diverging supersonic nozzle with a normal shock. The initial implementation has resulted in positive feedback from students and an improved self-efficacy in understanding and modelling complex thermodynamic systems not presented in class.

Introduction

The solution of problems involving complex thermodynamic systems often occupies much of a student's time and can be a distraction from them developing a clear understanding of system components, interaction of subsystems, modelling simplifications and assumptions, and design optimization. Refocusing students on the fundamental concepts of thermal systems design and analysis is possible with the introduction of system modelling software that carries some of the load of repetitive calculation required for complex systems. In addition, students typically learn how to use engineering modelling software in a Numerical Methods or Engineering Analysis course but often do not use those tools in subsequent courses and lose many of the acquired skills from those courses. Several computer modelling platforms, most of which were familiar to students, were introduced to the students enrolled in an advanced engineering thermodynamics course as useful aids for completing homework assignments and for the first semester project. After students became comfortable with using some of the analysis tools, listed in Figure 1 and shown in Figure 2, they were challenged to develop their own modelling tool for use in a supersonic nozzle design project. A survey of student perspectives on the various modelling tools developed by the students was used as an evaluation tool to help determine the most effective platforms for future projects and to expose students to a variety of analysis tools.

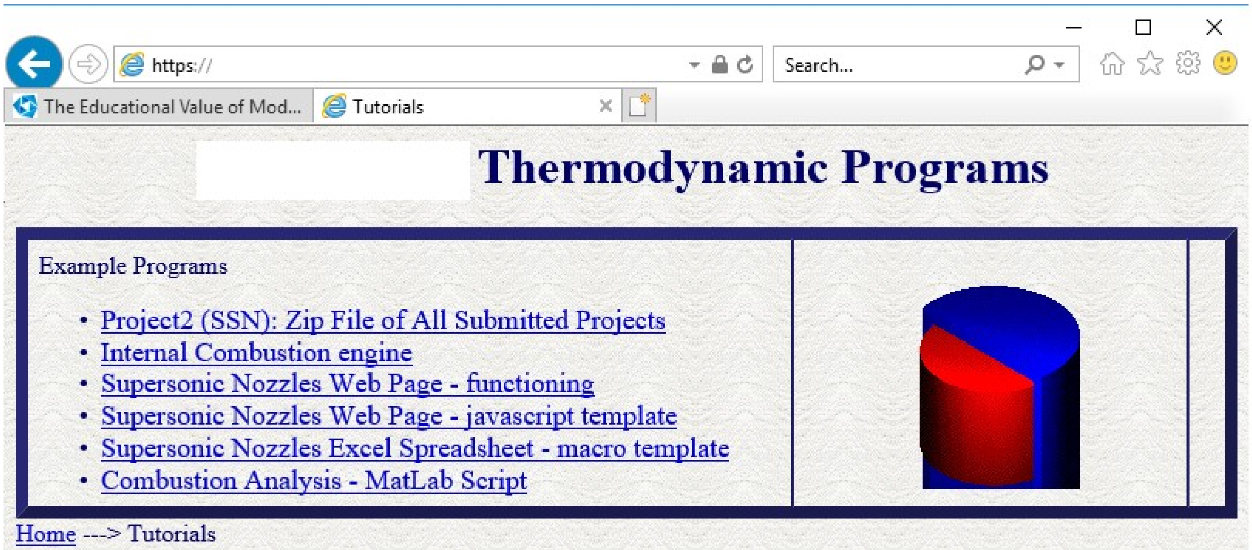

Figure 1: Web Site with sample programs for evaluating thermodynamic systems of equations

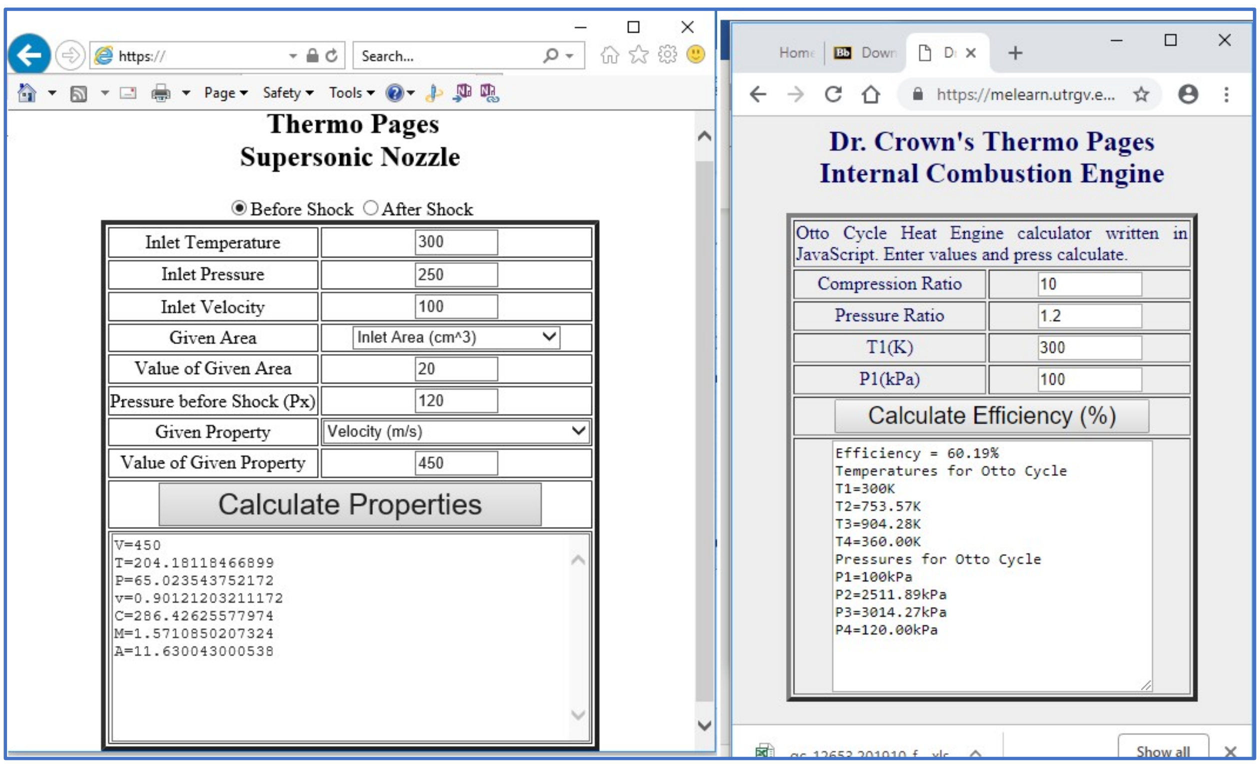

Figure 2: Samples of web page platform for thermodynamic systems (supersonic nozzle and IC engine)

Project Assignment

For many years, in an advanced undergraduate thermodynamics course, students have been using Visual Basic programs integrated with Excel spreadsheets to evaluate and optimize a variety of thermodynamic systems. Such projects have included advanced models of complex steam power plants, internal combustion engines, gas turbine power plants, refrigeration, and building energy systems. The projects have been useful learning tools for students in the course but represent a modelling platform (Excel macros using Visual Basic) that is not familiar to the students as it is not used or introduced in other engineering courses. Others [1], [2] have successfully used Excel spreadsheets as a platform for modelling, solving, and optimizing systems of engineering equations for a variety of problems. More common modelling platforms used by faculty and evaluated as an instructional tool for student learning that have been used in the classroom include Engineering Equation Solver (EES) [3], [4] and MatLab [5] - [7]. One challenge that must be faced when using software with thermodynamics problems is the determination of properties without the use of tables and figures. In each of the software applications referenced above, the function of determining thermodynamic properties either existed (EES) or was an add-on feature available (MatLab) or developed (Excel) for the software. A possible advantage to using software is that engineering problems requiring a higher level of mathematical complexity may be studied. In a study on the use of MatLab with an electronics course to introduce students to chaotic behavior in a Colpitts oscillator, the faculty note that without software "we have chosen to stay away from circuits that require a degree of mathematical sophistication beyond the undergraduate level" [8].

A new class project was introduced in the course to expose students to a variety of analysis platforms and to determine if a more familiar platform would yield similar or better results. Students were given the option to choose from a variety of software platforms including Excel, LabView, MatLab, SciLab, Javascript Web Pages, and C++. Students formed small groups of no more than four to five students per group and selected a platform to use for the project. Thirteen projects were developed by the 66 students in the course that represented all the previously listed software platforms.

Valid everywhere	Not valid across the shock
$\rho = \frac{P}{RT}$ $\dot{m} = \rho A\vec{V}$ $C = \sqrt{kRT}$ $M = \vec{V}/C$ $T_2 = T_1 + \frac{\vec{V}_1^2 - \vec{V}_2^2}{2C_p}$ $\frac{T_2}{T_1} = \frac{1 + \frac{k-1}{2}M_1^2}{1 + \frac{k-1}{2}M_2^2}$	$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{k}{k-1}}$ $\frac{A_1}{A_2} = \frac{M_2}{M_1}\left(\frac{T_2}{T_1}\right)^{\left(\frac{1}{2}+\frac{1}{k-1}\right)}$ Only valid across the shock $M_y = \sqrt{\frac{(k-1)M_x^2 + 2}{2kM_x^2 - (k-1)}}$ $\frac{A_y^*}{A_x^*} = \frac{P_{0x}}{P_{0y}} = \frac{M_y}{M_x}\left(\frac{T_y}{T_x}\right)^{\left(\frac{1}{2}+\frac{1}{k-1}\right)}$ $\frac{P_y}{P_x} = \frac{1 + kM_x^2}{1 + kM_y^2}$

Figure 3: Compressible flow equations for nozzles and diffusers

Semester Design Project #2 Thermodynamics II

Draft Due Date: Thursday, November 1st
Final Due Date: Tuesday, November 13th

Objective: This project will demonstrate your ability to use computer software to solve a complex thermodynamic system (supersonic nozzle) modeled with several non-linear equations that are solved using numerical methods in some cases.

Project Description: Your group (5-7 students) will design a program using the assigned platform (Excel, Web page, MatLab, SciLab, LabView, Simulink) that makes is easy to solve a converging/diverging supersonic nozzle with a normal shock in the diverging section. The program must be able to simply solve problems such as HW9-1, HW9-2, related example problems in the book, and former exam questions on nozzles. In addition to posting the program, you must also supply a one-page manual that explains how to use the program effectively. Your group will be graded on the items given below. The project is worth 7% of your final grade.

Graded Items (10 points each)

A) ____ Accuracy of calculations upstream of shock
B) ____ Accuracy of calculations across of shock
C) ____ Accuracy of calculations downstream of shock
D) ____ Ability to specify either sonic throat area or inlet area
E) ____ Ability to specify any desired property (V,T,P,v,A,C,M) and discover remaining properties
F) ____ Appropriateness of code
G) ____ Flexibility (can it solve several types of nozzle problems)
H) ____ Ease of use for solving problems
I) ____ Quality of one-page manual (promotional page)
J) ____ Reviews by other students

The user must specify the following:

1) Temperature, Pressure, and Velocity at a given state before the shock
2) The area at the inlet or the sonic throat
3) The pressure at the shock (Px) if a normal shock exists
4) A given property (V,T,P,v,A,C, or M) at a state of interest and whether it is before or after the shock

The program must easily calculate the following:

1) Stagnation properties (To, Pox, and Poy)
2) All properties at a defined state (V,T,P,v,A,C,M)
3) The mass flow rate
4) All properties at State X and State Y given Px

Figure 4: Assigned project to develop generalized computational tool for supersonic nozzle problems

The specific project was to develop a computational tool for designing and evaluating converging-diverging supersonic nozzles. The project assignment followed class lectures on the topic covering the fundamental linear and non-linear system of equations used to evaluate compressible flow in high-speed nozzles shown in Figure 3. The students were assigned several individualized homework problems online, delivered through an electronic homework system developed specifically for the course [9], that encouraged them to work out their own individual solutions. One of the homework problems requires iterating on a variable as the desired variable cannot be solved for explicitly. The complexity of solving a system of ten equations, several that are nonlinear, to solve for as many unknowns, with some requiring that they be solved numerically, sets the stage for introducing computer software as a computational tool. The assignment, shown in Figure 4, revisits the familiar course-homework assignments and demonstrates the power of a computational tool for solving very specific problems. In addition, students must develop a tool that can address all possible homework problems related to supersonic nozzles. This robust homework-problem solver encourages the use of functions, modules, and stable numerical methods for dealing with the non-linear equations.

Students Surveys

As part of the project assignment, students were asked to complete a survey of their own project in addition to evaluating projects from two other groups. All the group projects were made available online after the due date so that students could use the developed software and test it against the familiar homework problems and any other random nozzle problems they wished to evaluate. One objective was to get the students perspectives on alternate platforms, so they were required to evaluate at least one other group project that used a different platform from their own. The survey questions are shown in Table 1. The first six questions in the table (question D-Q5 was a duplicate of D-Q3 and is not shown) were only included in the evaluation of the student's own project. For these self-evaluations, the student is referred to as "Developer". The final seven questions in the table were included in the self-evaluation surveys and in the evaluation of the other group projects. For the evaluation of other group projects, the evaluator is referred to as "User". The "D" notation in the Number column (i.e. D-Q11) denotes questions that primarily relate to using the tool as a developer or someone who would modify the code to adapt it for a similar problem. The "U" notation in the Number column (i.e. U-Q8) denotes questions that primarily relate to using the tool developed to solve specific nozzle problems. The "Label" column is a keyword for each question in the graphs of survey results.

Table 1: Student survey questions for class project

Label	Number	Question Text
FILE	D-Q1	What is the filename of your group's project as listed in the zip file?
PLATFORM	D-Q2	Which platform did your group use for the project?
TIME	D-Q3	How many hours (total of all members) did your group spend on the project?
FINISHED	D-Q4	What percent (0 to 100) of the project did you successfully complete?
UNDERSTAND	D-Q6	The project helped me understand supersonic flow.
ENJOYED	D-Q7	I enjoyed working on this project.
CODE	D-Q11	The code used in the program is easy to use and follow.

DEVELOP	D-Q14	I would consider using this platform to develop other programs on my own to solve engineering problems.
EASY-TO-USE	U-Q8	The developed program is easy to use and understand.
HOMEWORK	U-Q9	The developed program is helpful for solving the homework problems.
NOZZLES	U-Q10	The developed program is useful for solving any general nozzle problems.
HANDOUT	U-Q12	The handout was easy to understand and helped me get started with the tool.
ENGINEERING	U-Q13	I would consider using solutions developed on this platform to solve engineering problems.

Each group member was asked to complete a self-assessment survey of their own project. Groups were typically composed of 4 to 5 students and each was assigned to complete their own evaluation. Of the 66 students in the class, 46 students completed the self-evaluation survey. Of the thirteen completed projects, five groups used the MatLab platform, three used Excel, two used JavaScript web pages, and the remaining platforms (C++, SciLab, and LabView) had one group each. One of the MatLab groups used SimuLink, however, the program was simply a MatLab script embedded in SimuLink and was, therefore, evaluated with the other MatLab groups. All questions on the survey used a 5-point Likert scale except for questions 1-4. The mean and standard deviation for each question was determined from the responses, and the number of standard deviations from the mean calculated for each platform. Surveys from different groups using the same platform were pooled.

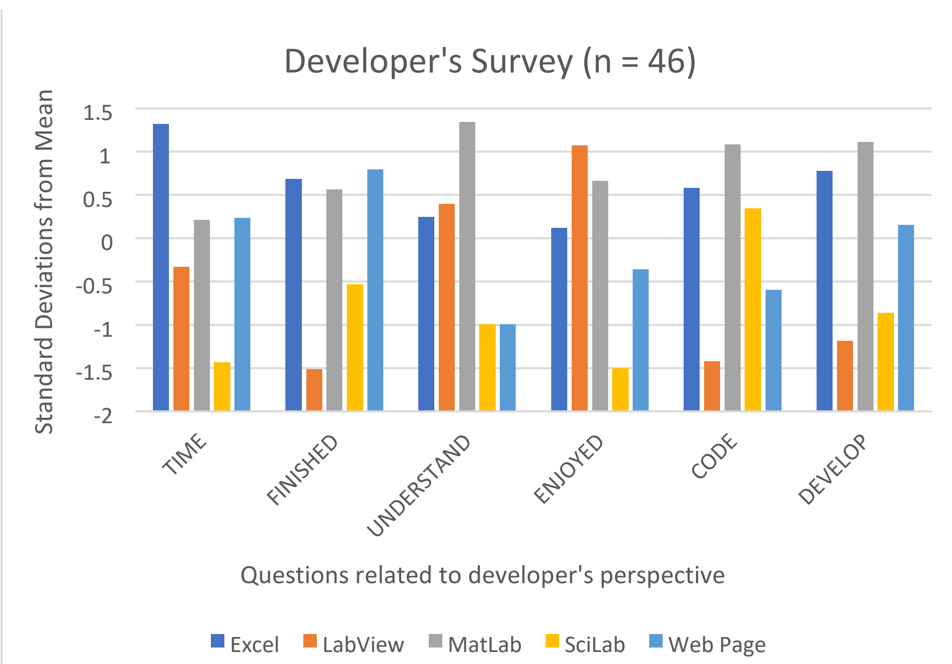

Figure 5: Survey results related to project development (self-evaluation)

Figure 5 shows the results of the self-assessment (Developer) survey for questions related to a developer's perspective such as time (hours) to develop the tool for evaluating supersonic nozzles. The values for "TIME" show a positive value if the required time for development was less than the mean value. The mean development time for the projects (total hours for the group) was 20.7 hours. If divided evenly for a typical group, this represents about 4 hours/group member, which is appropriate for the project. A single student worked on the C++ platform and reported 120 hours. Since the platform had only one evaluator, it was not included in the survey results. The "FINISHED" values show a positive value for the fraction of tasks completed above the mean. The mean value was 65% of the assigned tasks. All other results in the graphs are based on a 5-point Likert scale and show the number of standard deviations that they differ (positive and negative) from the mean value. The higher values represent a value closer to strongly agree. The Likert values for the four questions in Figure 5 are shown in Figure 6.

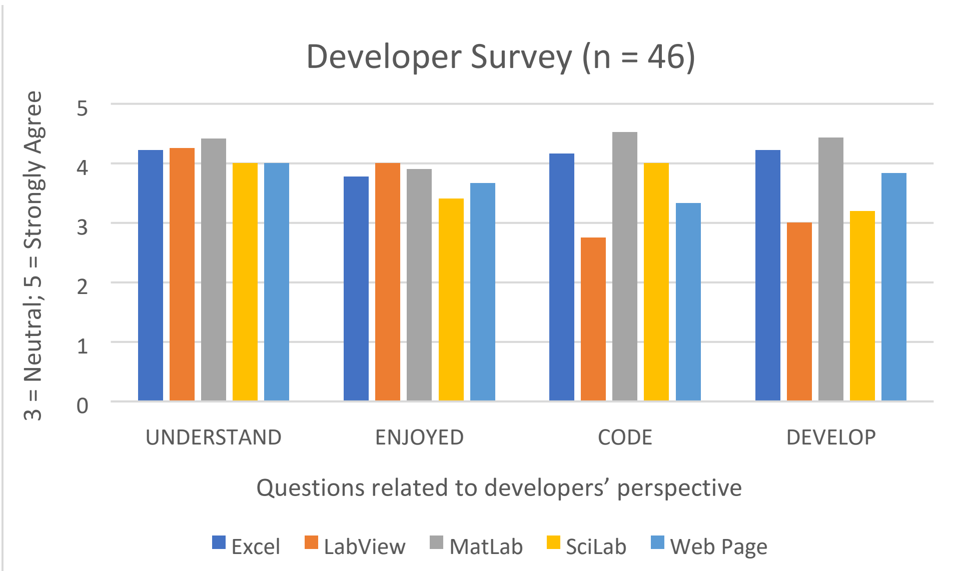

Figure 6: Survey results related to project development (self-evaluation/Likert scale)

The results from Figure 5 show that there are differences in how students responded to the various software (platforms). However, Figure 6 illustrates that though there are differences, the responses are positive with most students responding that they agree with each question. Their responses indicate that they grew in their understanding of supersonic flow in nozzles and enjoyed the project. Refer to Table 2 for student comments on how this project improved their overall understanding. There may be a variety of reasons for the differences, but the program that they are most familiar with (MatLab) compares favorably with the others. This was also the platform that the greatest number of students selected for their project. The variation and small differences in some of the results may also suggest that giving students a choice has some benefit and reduces undesirable collaboration between different groups.

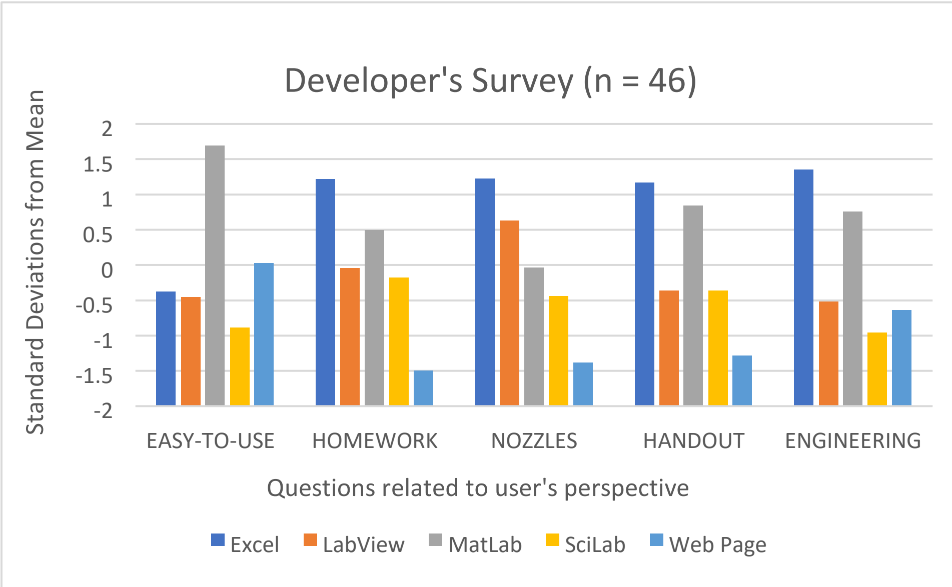

Figure 7: Survey results related to user experience (self-evaluation)

The self-assessment (Developer) results from the perspective of a user are shown in Figure 7. In this case, the Excel platform appears to show some advantage from a user's standpoint. This is significant as the primary motive for developing a computational tool is typically to use it to solve problems after investing in the development. However, from the perspective of students working on the project, they are likely more concerned with getting it done quickly and correctly than on using it after it is turned in.

Students were asked to complete surveys of two other group projects with at least one that implements a platform different from one they used for their project. A total of 92 surveys of other projects were submitted and evaluated. The surveys are given the title "User's Survey" as the evaluator did not develop the tool being assessed and is primarily focused on how it works over how it was developed. However, some of the evaluation questions for the user ask them to evaluate how the platform would be useful as a development tool. The results of those questions are shown in Figure 8. In this outsider view into the details of the program, the survey seems to indicate a preference for the Excel program. It is interesting to note that the JavaScript code also evaluated favorably given that most students indicated that they are not familiar with JavaScript at the time that they were selecting their groups' platform.

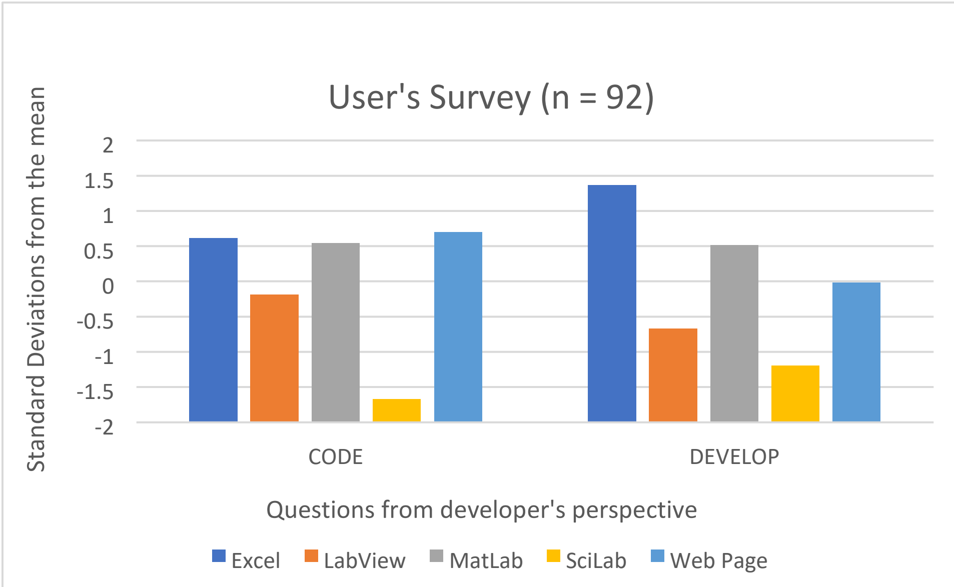

Figure 8: Survey results related to project development (evaluation of other groups)

Figure 9 shows the results for questions closely related to user features. These results are more significant for evaluation as to the adoption of a tool as the developer's self-evaluation is likely somewhat biased. Although the Excel platform compares favorably in both the "Developer" and "User" surveys, there is a significant rise in the values for the LabView and Web Page platforms in the "User" surveys. That is not surprising for the web pages as that is a platform that every student uses daily. LabView is only used in one course in the curriculum, but it may coincide with the thermodynamics course. The opportunity to see it applied in another course may have piqued their interest.

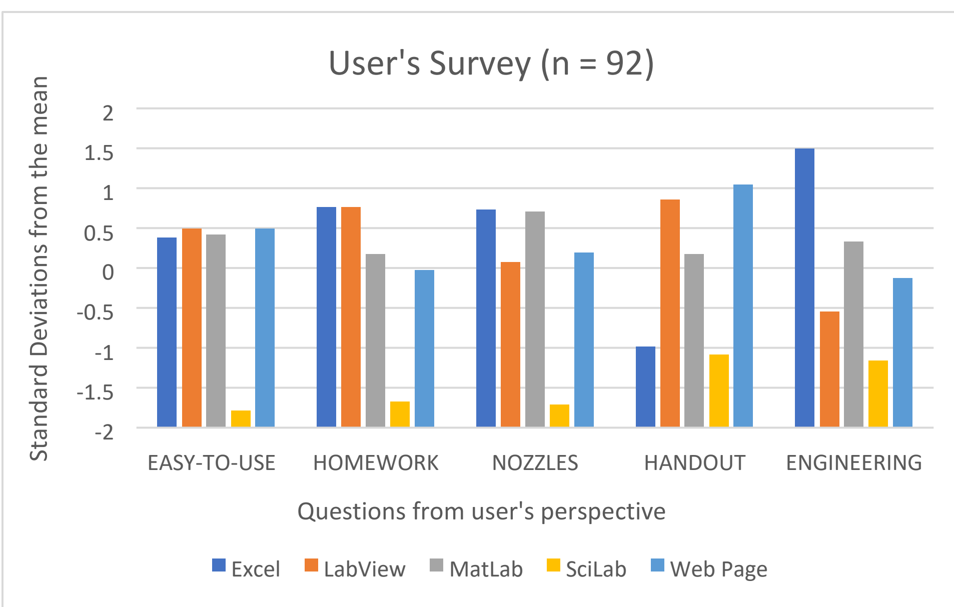

Figure 9: Survey results related to user experience (evaluation of other groups)

The survey gave students the opportunity to add additional comments about the project. A representative sample of the feedback is listed in Table 2. The comments reflect many of the same results already presented from the survey, but also show some of the positive learning outcomes of the project from the student's perspective. Some of the students found the project difficult, but also found it a useful and effective method for gaining a deeper understanding of a complex thermodynamic problem. Several students expressed difficulty with JavaScript pages and expressed that the webpage platform was a challenge for students. In the current semester, all students were assigned the webpage platform to determine if additional support could address student difficulties using this platform. The advantage is that students were most interested in the webpage platform in concept but had the most difficulty with implementation for this platform.

Table 2: Student Comments from Project Survey

#	**Comments: Survey Question 15**
1	I think most students only know how to use MatLab and Excel, and that's what makes the project difficult because most students do not know how to work with the other programs that are available.
2	The idea of incorporating computer coding software in this class is one of the best ideas ever.
3	The problem with this project is everyone worked on developing their own code on their own then they were compared to each other's codes. I do not believe that it was a good group project.
4	It was very time consuming but manageable.
5	The Webpage option became very difficult to try to figure out as nobody in the team had programming experience outside of MatLab, leading to various difficulties in terms of how to translate our formulas into the JavaScript code of the webpage. I believe the webpage option should be removed altogether from the possible programs to select from.
6	I would recommend you keep this project for future semesters, I feel like I mastered very well the nozzle equations since I was using them so much doing this excel program. All in all, I would advise you keep doing these types of project, I had a lot of fun doing it, it really opened my eyes on how using these tools can make our life's as engineers easier.
7	This project helped me learn more about nozzles and about programming. Although it was a bit challenging to edit the macros, in the end it was worth the hassle.
8	This was a great opportunity to get practice at coding and enabling our critical thinking skills, which I strongly believe is something all courses should strive for.
9	I personally didn't like this project it was very time consuming and was close to Exam 2.
10	It was a real challenge in breaking up the thermodynamics formulas and putting them into the program and make sure it gave the precise answers. This program does have a potential to really help students in solving problems. Hopefully, in the near future, I can make a prototype application for this program so students can actually use them for school.
11	I felt that the project was fair. I just wish my partners had helped me develop the code/put more effort into the project.
12	Learned a lot of new functions of MatLab such as importing files and interpolation function.
13	The project was very cool, my main comment is that perhaps having teams being able to use the same program, especially since my group had LabView. I truly enjoyed developing programs that help answer these types of problems.

14	This project helped me to develop more skills in MATLAB. Even after taking numerical methods, this kind of problems are not seen in that class. My team and I have to look for a variety of codes to complete the assignment. I am happy with what we reached and what we learned.

Conclusions

The project was well received by the students and they indicated that it helped them better understand the course content. The results may be of particular interest to those making decisions about the appropriate use and selection of various computer analysis tools. Although there are differences in how the students evaluated the various platforms, each of them had a unique set of advantages and disadvantages. One obvious parameter that was not a part of the survey was accessibility and cost as all the platforms were made available to the students.

The structure of the modelling software forced students to setup problems in the same way as if solved on paper but allowed them to identify common components and processes that could be modeled by common blocks and used in multiple thermal systems. The initial implementation has resulted in positive feedback from students and an improved student ability to understand and model new systems not presented in class. The instructor will continue to use a combined approach of Excel, MatLab, and JavaScript web pages as examples for the students and let them complete projects utilizing the platform of their choice.

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