Development and evaluation of a virtual learning tool to enhance comprehension of energy concepts

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***Abstract*—This innovative practice full paper presents the development and evaluation of a virtual learning tool. To provide a stimulating environment, a semester-long project is designed (as a part of an introductory Thermodynamics course) that requires students to design a virtual power plant. The project includes a range of tasks that provide students an opportunity to understand various aspects involved in construction of a power plant such as: choosing a geographic location for the power plant based on energy demands, examining economic and social impacts involved in construction of a power plant, and performing design calculations on individual components of the power plant. To aid students' understanding of the abstract engineering concepts involved in this project, a *virtual objects* (vObjects) tool is developed that includes animations, videos, and power, efficiency and design calculators. This article explains the tool development process (code and rationale), testing of the tool, tool refinement, and analysis to evaluate the effectiveness of the tool. The vObjects tool is developed using the LabVIEW software from National Instruments. Based on the analysis, the tool is found to improve the conceptual understanding of the topics in the course. The overall objective of this work is to understand the effectiveness of virtual learning environments. Results from the usability study suggest vObjects tool is user friendly and intuitive to use by undergraduate engineering students. Further, this tool can be used or modified for pedagogy of various science or engineering courses from K-12 to college where the use of physical objects is limited.**

Keywords— virtual learning environment; virtual objects; thermodynamics; power plant; LabVIEW.

I. INTRODUCTION

Various research studies [1-3] have provided empirical evidence that the use of physical objects can enhance engineering instruction through interactivity and visualization. Although physical objects can be helpful for stimulating learning of fundamental concepts, the usage of physical objects in educational settings is not often feasible in many science and engineering fields due to constraints such as size, safety, cost, etc. Thus, there is a need and opportunity for the development of a feasible alternative or supplement to physical objects. Virtual objects (in our study, referred to as vObjects) are an efficient replacement of physical objects. vObjects are three dimensional virtual (computer generated) entities that have geometric, functional, and behavioral characteristics developed to replicate physical objects (or systems) for students. A virtual environment that adapts reality is also found to simplify learning by highlighting only the salient information and removing confusing details [4]. Virtual learning tools are especially useful in helping students conduct experiments and to demonstrate concepts that are often difficult to illustrate or explain in a classroom environment. Toth et al. [5] used virtual laboratories to teach concepts in Biology and had the advantage of offering cost-effective alternatives to physical laboratories. McElhaney et al. [6] used virtual laboratories to give students the opportunity to investigate a complex physics topic – car collisions – that would otherwise be challenging to study in a classroom setting. Likewise, the use of simulations and modeling tools to teach abstract science and engineering concepts has gained popularity among researchers to understand how students could construct meaning through these tools [7, 8]. The effectiveness of computer simulations in students' learning was further explored and affirmed by De Jong et al. [9] and Magna et al. [10].

Pedagogy based on a *situated perspective on learning* supports pragmatic learning through group activities which is especially applicable in the field of engineering. Several researchers have supported situated learning for engineering: Hammond et al. [11] explain that a stimulating learning environment that includes tasks, feedback, and the learner's involvement all influence the learning process. Sheppard et al. [12] suggest that in order to prepare engineering students for real-world engineering practice, the education method should include projects that allow students to apply concepts introduced in the classroom (situated learning). Jarvis [13] postulated that significant learning occurs when the learner perceives the relevance of the subject matter. Learning by doing is found to serve as a platform for experiential learning. In Kolb's method of experiential learning [14], the learner i) is actively involved in the experience, ii) reflects on the experience, iii) has the skills to conceptualize the experience, and iv) uses new ideas gained from the experience for problem solving. These studies strongly suggest that *situated learning* is an excellent method for illustrating and explaining difficult or abstract concepts. In the current work, situated learning is adopted by allowing students to work on a real-world engineering project with a broad objective, related to thermal sciences.

Streveler et al. [15] identified thermal sciences as a field that poses challenges in conceptual understanding. One particular course, *Engineering Thermodynamics*, is known to be challenging and is taught across multiple engineering disciplines during the sophomore and junior years of undergraduate engineering studies. Several concepts in thermodynamics such as temperature, heat, energy, enthalpy, and entropy, are abstract and are somewhat difficult for students to comprehend leading to significant misconception of the fundamentals. To further add to the conceptual difficulty, the use of many physical objects that operate based on thermodynamic principles (such as turbines, pumps, and boilers) in a classroom is not possible due to size, cost, and safety. Therefore, thermodynamics is a domain of study that could make use of vObjects. Apart from the limitation of using physical objects, a majority of engineering courses (including thermodynamics) require students to examine well-defined problems that yield straightforward solutions. However, in real-world scenarios, the problems encountered in engineering practice are complex and ill-structured as opposed to classroom learning [16-18] and require multiple approaches to solve them. Such ill-structured problems pose challenges to students in structuring, developing, and evaluating solutions [19].

Therefore, in the present study, a real-world semester-long project with multiple tasks (situative learning) in the course, Thermodynamics (an abstract, challenging engineering course) is put forth to the students. To help student understand the abstract concepts and successfully complete the project, a virtual environment tool is developed. The overall objectives of this work are to:

a) Develop a vObjects tool that includes videos, animations, and calculators to help students understand various thermodynamics concepts required to complete the course project, and
b) Analyze the effectiveness of the vObjects tool by evaluating reports of students (from different semesters) who completed the project with and without the tool. The reports are evaluated based on a 10-point rubric (explained in a later section).

This paper addresses the first of the two objectives: the tool development process and the associated rationale are explained. The second objective of analyzing the effectiveness of the tool, is done in two stages. In the first qualitative stage, the tool is piloted by two undergraduate students who had completed the course without using the tool. Feedback of the students' performance is obtained from the course instructors. The second qualitative assessment stage includes a detailed statistical analysis (an experimental design including MANOVA, hierarchical regression), to understand the effectiveness of the tool. The results from the statistical analysis and the qualitative effectiveness of the tool will be part of a separate manuscript published later.

While the vObjects tool developed in this work focuses on an Engineering Thermodynamics course at the undergraduate level, these types of tools can be extended for teaching other engineering or K-12 courses with abstract concepts. The current tool could be used as a template for any situated learning course project.

II. TOOL DEVELOPMENT - CODE AND RATIONALE

The vObjects tool is developed using the commercial software package, LabVIEW from National Instruments, as it provides versatility in creating animations, embedding videos and images, and building calculators required to solve various equations. LabVIEW also provides the flexibility of developing the tool for computers operating in both Windows (.exe) and Mac (.app) operating systems. The development platform of LabVIEW has two components: the *front panel* and the *block diagram*. The front panel (1) functions as the Graphical User Interface (GUI), and it contains buttons, images, videos, animations, and all of the controls and user inputs to the tool. The second component is the block diagram, and it contains the graphical source code for the LabVIEW program. Each component from the front panel is represented by a terminal in the block diagram. Together, the front panel and the block diagram constitute a *Virtual Instrument* (VI). In addition to these developed VIs, LabVIEW has built-in sub-VIs to perform specific common tasks such as opening or writing to a file, playing a video, etc., and these sub-VIs are applied in the tool development.

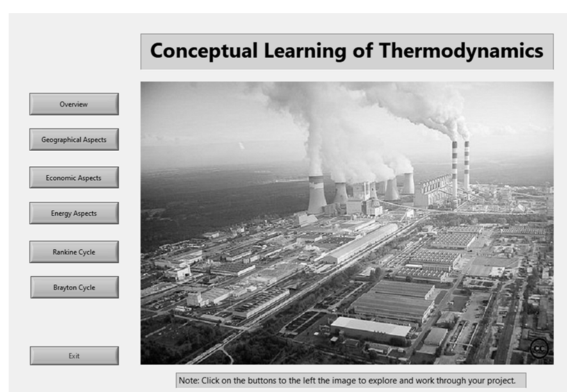

Fig. 1 Sample of the front panel

The tool is primarily divided into six sub-segments, and each one addresses an objective of the course learning objectives. From an organizational perspective, each of these segments appears as a sub-VI (a new window) which can be accessed from the main VI (home window). This structure is explained in the subsequent sections.

A. Design of the Overview Page

The *Overview* window provides a situated learning platform to help the student with a holistic view of the population-energy-economy relation. A graph displays the estimated population growth until the year 2050, and adjacent to this chart is an image that shows how the growing population requires an increase in energy consumption. A chart is included to connect the global energy requirements with that of how the economy drives this demand (front panel shown in Fig. 2). The Overview page is accessed using its corresponding Boolean button (Overview*)* in the front panel of the home page (Fig. 1). The image on the left of Fig. 2 provides a flow chart of how the increasing population results in higher energy demand and the trend in global population increase, while the image on the far right panel indicates how the Human Development Index (HDI), an indication of quality of life [20], relates to electricity consumption. Further, to help students understand the key concepts of Gross Domestic Product (GDP) and GDP per capita which indirectly drives energy demand, a link to a video is provided through a Boolean button

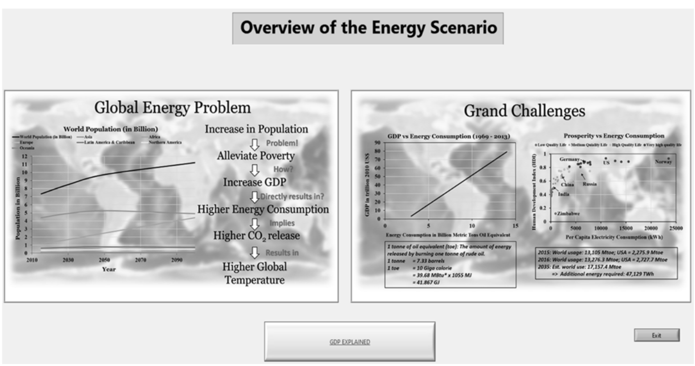

Fig. 2 Window displaying the overview of the global energy problem connecting population increase with GDP and energy consumption. This window is designed to provide students with an overview of the course main learning objectives

B. Design of the Geographic, Economic, and Energy Aspects

The first set of objectives of the course project is designed to provide the students with a holistic viewpoint on the construction of a power plant. Students are required to address the following objectives:

a) Need for additional energy and projections of energy demand,
b) Economic situation of the site being proposed,
c) Resources available, and
d) Economic and societal impact of constructing a power plant.

To address these objectives, three sub-VIs are created, namely, Geographic Aspects (Fig. 3), Economic Aspects (Fig. 4), and the Energy Aspects (Fig. 5), all of which are accessed from the front panel of the home page (Fig. 1) using their corresponding Boolean buttons. The front panel design (Fig. 1) is identical for all three cases with just the image containing the data modified. The main page (for all three aspects) has a drop-down menu (Fig. 3), which lists the three countries of interest. When a country is selected, the page displays two images (Fig. 4). The image on the left displays the current data, and the image on the right contains the predicted data, in terms of energy and economy. These graphs provide the students with trends in terms of energy demand, available resources, and economic growth. The data in conjunction with the understanding obtained from the Overview window, helps the students choose a site for the construction of the power plant. The list of parameters highlighted in the tool (present and predicted) in these three aspects are listed in TABLE I.

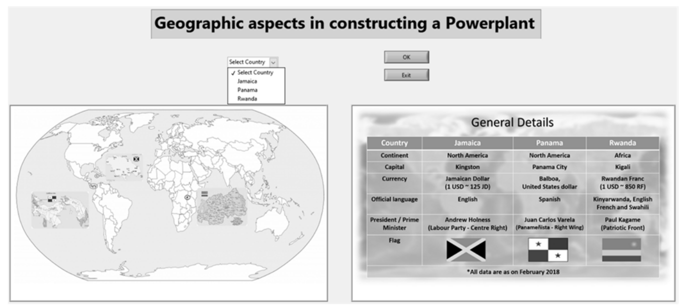

Fig. 3 Generic home page for Geographic, Economic, and Energy Aspects. The country of choice is selected from the drop-down menu.

TABLE I Parameters considered in Economic, Geographic, and Energy aspects

Economic aspects	Geographic aspects	Energy aspects
GDP	Population	Total Energy Consumption
GDP Composition	Land area	Energy consumption per capita
GDP per capita	Water area	Total energy production
Unemployment rate	Number of rivers	Energy import
Inflation rate	Renewable water resources	Energy export
Exports value	Agricultural land	Population without electricity
	Temperature range	

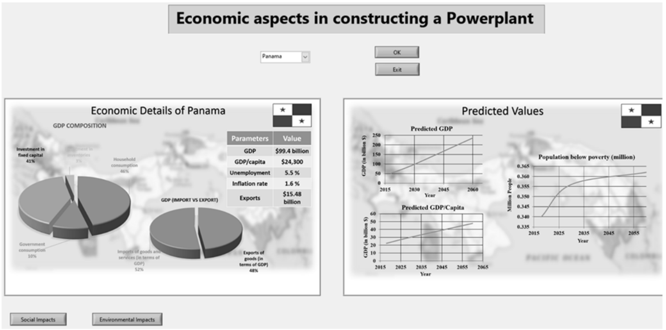

Fig. 4 Window (front panel) displaying the current (left) and future (right) economic trends of a country using graphs.

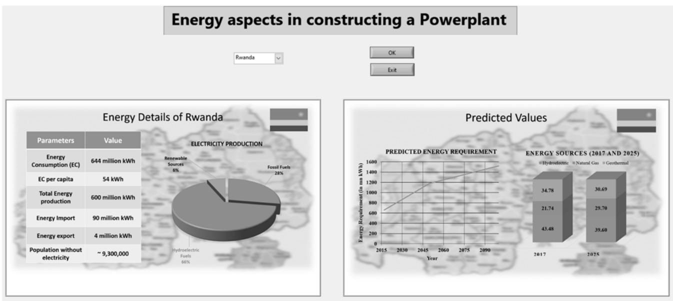

Fig. 5 Window (front panel) displaying the current (left) and future (right) energy demands of a country using graphs.

C. *Design of the Rankine and Brayton Cycles page*

Once the need for a power plant and the impacts of such a power plant are examined, the next set of objectives for the students are to design the working systems and components of the power plant. Students are required to design the power plant operating on a Rankine (working fluid is water) or Brayton (working fluid is air) thermodynamic cycle with the following objectives:

a) Determine the overall specifications such as the maximum theoretical efficiency of the system and the estimated cost and duration of construction.
b) Sketch process diagrams such as pressure vs. specific volume (P-v) and temperature vs. entropy (T-s) of the system along with component diagrams that include pumps, boilers, etc. with critical points marked along with their temperatures and pressures.
c) Mass flow rate(s) of the working fluid(s) required to achieve the targeted power output for the system.

To address these objectives, individual VIs are created for the Rankine and Brayton cycles which are accessed from the home screen of the tool (Fig. 1). The current version of the tool has simple Rankine and Brayton cycles (without regeneration or reheat), however further complexity can be added by the students, if desired. The design of the front panels (Fig. 6 and Fig. 7) of these two VIs are identical. The front panel contains three animation blocks running simultaneously to explain the operation of the power plant (using the thermodynamic cycle).

The three animations explain the process diagrams, T-s relation, and the P-v relation, respectively. The animations run synchronously in the three blocks with the same process highlighted in each block (highlighted by dotted lines in Fig. 6 and Fig. *7*), and the current process is described with text below the animations. On understanding the theory of the thermodynamic cycles, students can examine the details of individual components within the cycle along with the appropriate energy conservation equations and their operating conditions (pressure and temperature).

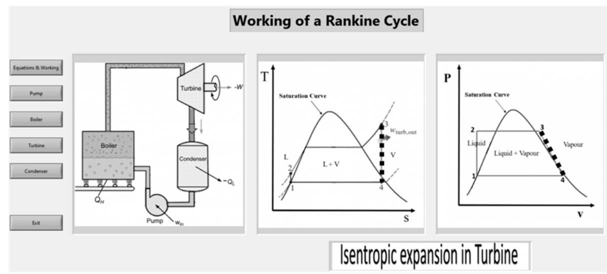

Fig. 6 Window (front panel) of the Rankine Cycle page that includes animations to explain the working of a Rankine Cycle. The window includes buttons to access each sub-component associated with the cycle.

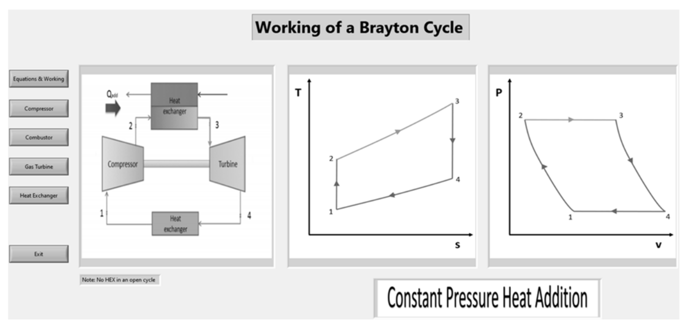

Fig. 7 Window (front panel) of the Brayton Cycle page that includes animations to explain the working of a Rankine Cycle. The window includes button to access each sub-component associated with the cycle

D. *Design of the Equations and Working Page*

The first sub-VI in the thermodynamic cycle VI describes the processes involved in the cycles and the associated equations used for design calculations. The front panel (Fig. 8) consists of three images: one each for the schematic of the cycle, the thermodynamic processes, and the mass flow rate calculations corresponding to the overall energy demand obtained from the first set of objectives. Additionally, to give students an understanding of the typical operating conditions (pressures and temperatures) of a power plant, a link to scientific articles explaining these parameters for the Rankine [21] and Brayton [22] cycles are provided, and are accessed using the Boolean buttons provided. The design of the front panel of the *Equations and Working* VI for a Brayton cycle is identical to the one shown in Fig. 8.

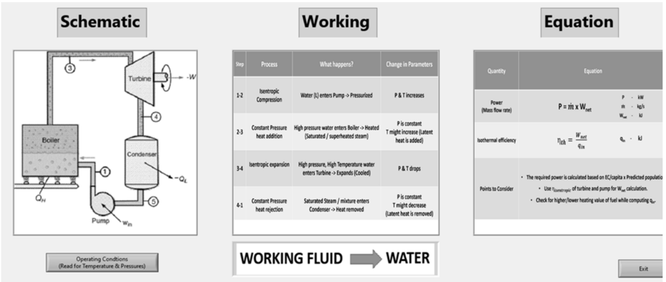

Fig. 8 Front panel of the Equations and Working VI for the Rankine Cycle.

E. Design of the Components Page

Within the thermodynamics cycle's page, sub-VIs are included to understand the operation of each component and a calculator is included to measure the associated work input or output. For the Rankine cycle, separate sub-VIs are created for the pump, turbine, boiler, and condenser, while for the Brayton cycle, sub-VIs are created for the compressor, combustor, heat exchanger, and gas turbine. The design of the front panel (Fig. 9) is identical for all these sub-VIs with their corresponding content.

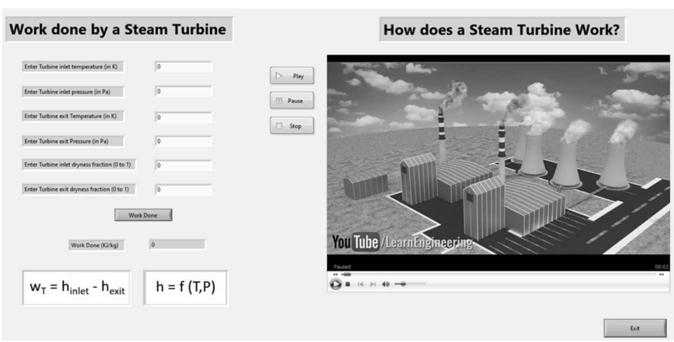

Fig. 9 Front panel of the Components VI (a steam turbine is shown in this case)

The front panel of a system sub-VI has two components. On the right side, a video explains the operation of the component, and, on the left, a calculator measures the work output (or input – for pumps and compressors). The video player has buttons to *play*, *pause*, and *stop* the video. The work output calculator requires the temperature and pressure at the inlet and exit. These values of temperature and pressure can be obtained using the journal article (mentioned in the previous VI) as a reference. The equations [23] to compute the work output (or input), is added as a text string.

III. Building the Application for Windows (.exe) and Mac (.app) Operating Systems

A system-independent executable file is to be created (.exe for Windows OS and .app for Mac OS), which does not require the installation of LabVIEW. To create this executable file for a computer operating on Windows Operating System (OS), a *new project file* is created by importing these VIs and the corresponding media files (images and videos). Using the *Build Specification* option, an .exe file is created with the home page VI (Fig. 1) as the *Startup VI* and all other VIs as *Always Included* support files. Additionally, an installer is built to enable a user to install this executable along with the necessary support files. During this process, to ensure that the LabVIEW VIs work as a stand-alone program without the requirement of installing LabVIEW, a LabVIEW *runtime engine* is added to the installer. By generating an installer, the tool is delivered as any other commercial software package with a *setup* file, which, on execution completely installs the tool. Similarly, to create an .app file that is compatible with Apple's Mac OS, the *build specification* option is used and an .app file is generated but with the *run-time engine* provided separately along with the installer.

IV. Results: Testing and Prelimenaly Evaluation of vObjects

The effectiveness of the tool is tested in two stages. In the first qualitative stage, the tool is piloted by two undergraduate students who had completed the course project without using the tool. Further, feedback of the students' performance using the tool is obtained from the course two instructors. The second stage includes a usability study with students who completed the course project using the tool.

A. Pilot testing

To pilot the tool, two undergraduate students who had completed the course project without the tool were asked to complete the objectives of the project using the tool. The following observations and feedback were reported by the students in the chronology of project objectives:

1. A better understanding of the holistic view in terms of connecting the energy demands and economic aspects. The tool provided a clear graph that elucidated how the growing population and improving economy directly resulted in higher energy demands (affirming the benefits of situated learning).
2. A student had requested an explanation of GDP and GDP per capita in the tool, as some students are unaware of these topics. To better explain these concepts, links to external websites are provided through the tool as was discussed in the previous section.
3. A request to provide a report (or a case study) to help understand the societal and environmental impacts on construction of a power plant. The tool now includes links to journal articles explaining the social [24] and environmental [25] impacts of constructing a power plant, accessed from the *Economic Impacts* page.
4. Students reported that the videos help in better understanding of the sub-systems (turbines, compressors, etc.) used in the Rankine and Brayton cycles. The design calculators helped them quickly check the variation in magnitude of work output or input by simply changing the operating conditions (e.g. temperature values) of the components.
5. Feedback was provided to include pressures and temperatures of the working fluid at critical points (from P-v and T-s diagrams) of an actual power plant.

As mentioned earlier, journal articles [21, 22, 26] are included in the vObjects tool to provide typical pressure and temperature values in operational power plants.

6. Suggestions for certain aesthetical improvements such as: requirement of major and minor gridlines in graphs to enhance extracting data, increased font size in graph legends, and contrasting colors for font and the background were made and these changes are included in the tool.

Feedback from the students were then used to refine the tool. In addition to the students' feedback, the feedback from the course instructor suggested that the tool is a good addition and supplement to the classroom instruction, and that it helped deliver content that was typically not covered in the course.

B. *Usability study*

To further evaluate the effectiveness of the tool, The IBM computer usability study was employed [27]. A group of 64 students who used the vObjects tool were asked to complete the Post-Study System Usability Questionnaire (PSSUQ), a well-established questionnaire aimed at measuring the usability of products with multidimensional characteristics. The PSSUQ contains 19 items measuring the following sub-scales: system usefulness (SYSUSE), measured by items 1-8; information quality (INFOQUAL), measured by items 9-15; interface quality (INTERQUAL), measured by items 16-18; and overall satisfaction (OVERALL), measured by items 1-19. The PSSUQ was administered to students after they used the tool in the course. Participants were asked to rate their responses to statements concerning their use of the vObjects app using a Likert-scale ranging from 1 (strongly agree) to 7 (strongly disagree). TABLE II shows the mean, standard deviation, minimum, and maximum values for the overall satisfaction scale (M = 3.64, SD = 1.33), the system usefulness subscale (M = 3.62, SD = 1.47), the information quality subscale (M = 3.53, SD = 1.33), and the interface quality subscale (M = 3.82, SD = 641.44). As shown in the table, the interface quality had the highest mean score compared to other subscales. The overall satisfaction scale represents the average score of all items (1-19) while the SYSUSE, INFOQUAL, and INTERQUAL subscales represent the average score of 1-8 items, 9-15 items, and 16-18 items respectively.

TABLE II Descriptive Statistics for the Questionnaire Scales

	Valid	**Missing**	**Mean**	**Std. Dev. (SD)**	**Min.**	**Max.**
Group	64	0	1.609	0.492	1.000	2.000
OVERALL	64	0	3.637	1.329	1.000	7.000
SYSUSE	64	0	3.615	1.473	1.000	7.000
INFOQUAL	64	0	3.533	1.329	1.000	7.000
INTERQUAL	64	0	3.818	1.444	1.000	7.000

Several statistical analyses were performed to assess the psychometric properties of the questionnaire. These analyses include exploratory factor analysis, reliability analysis, correlation analysis, and item-level descriptive statistics. The analysis revealed that all subscales had very good to excellent reliabilities. The Cronbach's alpha for the OVERALL scale, SYSUSE subscale, and INFOQUAL subscales were 0.967, 0.949, and 0.919 respectively. The reliability for the INTERQUAL subscale was 0.850.

The item-level descriptive statistics give quantitative measure whether respondents were satisfied or dissatisfied with what they were being asked about. The mean scores ranged between 2.8 and 4.0. The mean score for item 4 (SYSUSE) and item 19 (OVERALL) were the highest indicating that respondents tended to disagree with the statements "I was able to complete the project tasks quickly using this system" and the statement "Overall, I am satisfied with this system". Furthermore, the mean score for items 7 (SYSUSE) and item 13 (INFOQUAL) were the lowest indicating that responded tended to agree with the statement "It was easy to learn to use this system" and the statement "The information provided for the system was easy to understand".

V. Conclusions and Future Work

The use of physical objects has enhanced pedagogy of various engineering concepts. However, certain courses like Engineering Thermodynamics limit the use of physical objects and therefore the idea of using virtual objects becomes attractive. The focus of the current study was to help undergraduate students understand the concepts of engineering thermodynamics by completing a course project that requires students to design a power plant with the assistance of a newly created virtual objects tool. This paper explains the complete tool development process. The interactive tool provides students with an overview of subjects involved in the construction of a power plant (such as economic, environmental, and societal impacts) and understanding the thermodynamic concepts (power cycles and systems operating in the cycle). The concepts are delivered in the form of graphs, images, animations, videos, and calculations.

The initial quantitative analysis and the results from the usability study provide promising evidence of the effectiveness of using the vObjects tool. The researchers are currently working on a follow-up study to provide empirical evidence of the effectiveness of the tool, including a blind evaluation of students' projects (with and without the tool) by professional engineers working in the energy industry.

The virtual objects tool described in this work can be used as an additional pedagogy tool to enhance the learning of not only thermodynamics concepts but any engineering or K-12 course that involves challenging or complex concepts that are not easily demonstrated with physical objects. The current tool (made available on the ACE(D) research lab website, acedvt.com) can be used as a base code which can be modified based on the requirements of various courses.

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