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Pedagogical strategies for enhancing machine design teaching in a mechanical technology programme

Estrategias pedagógicas para mejorar la enseñanza del diseño de máquinas en un programa de tecnología mecánica

Carlos A. Romero-Piedrahita[1], Libardo V. Vanegas-Useche[2], Miguel Díaz-Rodríguez[3]

[1]Facultad de Tecnología, Universidad Tecnológica de Pereira, Colombia. Orcid: 0000-0001-5647-1918. Email: cromero@utp.edu.co
[2] Facultad de Ingeniería Mecánica, Universidad Tecnológica de Pereira, Colombia. Orcid: 0000-0002-5891-8696. Email: lvanegas@utp.edu.co
[3]Laboratorio MECABOT, Facultad de Ingeniería, Universidad de los Andes, Venezuela. Orcid: 0000-0001-7243-4957. Email: miguediazr@gmail.com

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Abstract

The aim of this paper is to present a reformed approach to the teaching practice of the Machine Design course offered in the Mechanical Technology Programme at the Technological University of Pereira. The course combines the concepts of rational selection of materials and strength of materials with the procedures to be followed to shape and dimension the classical elements presented in machinery and mechanical systems. Active learning, hands-on activities, laboratory sessions, practical examples, projects, teamwork and technological and virtual resources are used as a means to achieve effectively the learning outcomes. An important goal is to integrate strength and stiffness calculations with the engineering design process, including conceptual design, creativity, optimization, detail design and documentation. The use of technological tools, minor and main course projects, along with practical activities in the laboratory, are supposed to enhance the teaching process and help students acquire the desired competencies.

Keywords: active learning; curriculum; engineering education; machine design.

Resumen

El objetivo de este trabajo es presentar un método reformado de la práctica docente del curso de Diseño de Máquinas ofrecido en el Programa de Tecnología Mecánica de la Universidad Tecnológica de Pereira. El curso combina los conceptos de selección racional de materiales y la teoría de resistencia de materiales con los procedimientos seguidos para definir las geometrías y dimensiones de los elementos clásicos presentados en maquinaria y sistemas mecánicos. Se utilizan el aprendizaje activo, actividades prácticas, sesiones de laboratorio, ejemplos prácticos, proyectos y recursos tecnológicos y virtuales como medios para lograr de manera efectiva los resultados del aprendizaje. Un objetivo importante es integrar los cálculos de resistencia y rigidez con el proceso de diseño de ingeniería, que incluye el diseño conceptual, creatividad, trabajo en equipo, optimización, diseño detallado y documentación. El uso de herramientas tecnológicas, proyectos menores y principales, junto con actividades prácticas en el laboratorio, se supone que mejora el proceso de enseñanza y ayuda a los estudiantes a adquirir las competencias deseadas.

Palabras clave: aprendizaje activo; currículo; diseño de máquinas; educación en ingeniería.

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1. Introduction

Traditional machine design teaching consists of discipline-specific modules, with the lecturer playing the main active role. Likewise, in the Mechanical Technology Programme at the Technological University of Pereira, the Machine Design course has been taught following traditional textbooks [1-2]; these emphasize the detailed specification of machine components within the design process, addressing procedures for sizing of mechanical parts. The course has been taught through the introduction of theoretical topics first. Then, examples are explained, and several pieces of homework are assigned to allow students to develop their problem-solving skills. This conventional approach lacks the implementation of the complete engineering design process and the integration of other disciplines such as manufacturing, materials and economics. Additionally, the course structure has not generally promoted creativity or other required skills.

After some self-evaluation sessions within the Area of Solid Mechanics in the School of Mechanical Technology, faculty staff agreed that the pedagogical models have remained predominantly instructive. Thus, the necessity of enabling students to become more independent learners was recognized. As a result, a pedagogical reform was introduced to integrate various professional skills into the courses and particularly, to improve the pedagogical approach of the Machine Design course.

The faculty staff has reviewed a wide range of literature about engineering and technological design education [e.g., 3-34]. This was done to gain an insight into the evolving pedagogical models and the variables affecting the teaching of machine design and also, to construct a pedagogical framework for the course of Machine Design in the Mechanical Technology Programme. For space restrictions, this review is not included here, but it is presented in [35].

After reviewing and discussing the pedagogical trends in machine design education summarized in [35], it was acknowledged that the curriculum must be taught through planned teaching and assessment methods accompanied by environments created for the interaction with students. It is recognized that design should be at the core of the engineering curriculum. Thus, combined design educational practices must be conceived with design fundamentals integrated across courses, semesters and extra-curricular activities. Design experiences must be conveyed to students in a project-driven approach, procuring to simulate design, manufacturing, assembly, and operating processes. Emphasis should be placed on teamwork, communication, creativity, ingenuity and computer-aided design tools.

In the pedagogical model proposed, it is envisioned that objectives of the course can be accomplished through a balanced integration of topical lectures and active learning activities (section 2), practical works in the laboratory (section 3), "small scale projects" (section 4), main course project (section 5), industrial visits and field trips. The Machine Design course is built sequentially by accumulating specific knowledge and skills, leading to a main integrated design project that involves the core competencies. For the execution of the pedagogical model, a set of resources are foreseen including facilities for designing, prototyping, and manufacturing products (CAD/CAM, rapid prototyping, workshop, etc.).

2. Topical lectures and active learning activities

In general, the teaching method consists of lecturing, demonstrating, simulating, case studying, collaborating, exercise solving, and inquiring. The course notes must be available to the students, who must read them before class and come to it to discuss and deepen their learning.. When arriving at class, students are inquired about the topic and its relevance to their formation. The lecturer begins the class with a whole group discussion to refresh the previously assigned reading. With the inquiry-based or guided approach, the focus is placed first on the question, problem, challenge or goal to be addressed. Then, the lecturer presents the theory; that is to say, they explain the concepts underlying the integral dimensioning of mechanical components and transmissions, model, derive, and explain the equations and present practical examples.

For instance, after explaining the buckling phenomena in beams subjected to compression loads, the lecturer demonstrates it with the example of an engine connecting rod loaded with the resultant of inertial and gas pressure forces, followed by a short video or an animation of a simulated work. In tutoring sessions, additional practical examples are given and are related to the theory. Additionally, throughout the course, the lecturer assigns homework exercises and prompts the students to apply the concepts in a related small-scale project. Thus, the course of Machine Design is taught in such a manner that not only explores the fundamentals of the scientific behaviour of materials and machine elements but also imparts practical tools for designing and building machines.

During the lectures, workshops and open-ended design problems are planned as either an in-class exercise, a reverse engineering problem, a demonstration conducted by the lecturer or an assignment to the students. Students talk and listen, read, take notes, sketch and reflect as they approach course content through problem-solving exercises, informal improvised small groups, simulations, case studies and other activities for applying what they are learning. As an enhancement of their normal lecture, the professor encourages students to follow web-based and downloadable design tools, manufacturers' electronic catalogues, YouTube videos and websites with material specifications, engineering data, standards, equipment specifications, design repositories, and databases. Also, students interact with prepared worksheets that allow them to integrate their design and analytical thinking.

Lectures are presented by making use of PowerPoint presentations. Detailed project procedures and tutorials, files, links, spreadsheets and simulation softwares are employed to enhance student comprehension. To complement lectures, seminars with participation of machine component dealers and commercial representatives (roller bearings, belt and chain transmissions) are scheduled during the semester in extra time sessions. The lecturer proposes the students to perform the mechanical dissection of a familiar tool or scrap artefact acquired in a junk yard (electrical driller or grinder, jigsaw, compressor or drilling machine). This is done to motivate them to learn engineering concepts and also, to help them to acquire abilities to reverse engineer systems and develop engineering intuition. By interacting with real mechanical hardware outside the class, students reinforce the topics covered in class.

Electronic mail is promoted as well. It is suggested as a way to improve lecturer-student communication between classes, to extend topic discussions and to explore critical issues with students.

3. Practical and hands-on work in the Mechanisms and Machine Design Laboratory

3.1. Introduction

The goal of the laboratory activities is to teach basic and practical mechanical design knowledge. Learning activities are specifically designed to foster student exploration with real-world hardware, machines and physical systems, advocating "hands-on" and "minds-on" learning.

A list of practical activities are proposed to students to help them acquire abilities to identify machine components, measure dimensions and dynamical parameters, select components from catalogues, diagnose proper and abnormal behaviour, reverse engineer systems and develop engineering intuition. By interacting with real mechanical hardware, students reinforce concepts of statics, dynamics, machine theory and mechanics of materials. Small scale test bench simulators have been allocated to experimentally analyse the effect of force and moment loads on truss and beam arrangements (stresses, deformations and shape stability).

By putting into practice a discovery learning approach, with the aim of boosting student inductive learning, students are faced with real machine components and systems. They manipulate them and gain an insight and understanding in a cooperative environment. During the academic semester, six out of ten practical works in the course of Machine Design are to be performed by groups of 3 to 4 students in an allotted time of 2 hours a week. For the laboratory sessions, the modules and benches available are: (1) Introduction to Machine Systems, (2) Stress Measurements and Concentrations, (3) Gears, Gear Reducers and Power Transmissions, (4) Gear Reducer Test Stand, Fits and Tolerances, (5) Braking System Components, (6) Cut Model of an Automotive Powertrain, (7) Cut Section Model of a Hydraulic Pump, (8) Bearings, (9) Bolts and (10) Cylindrical Spring.

Before laboratory sessions, students are drawn by questions leading them to investigate different characteristics related to the operation of the machines. For instance, students are asked about the synchronizer operation in the automotive gear transmission, about the different speeds available for the drilling machine, about machine elements and operation principle behind the gear reducer test bench and about the operation as well as about the advantages and disadvantages of chain and belt transmissions.

3.2. Introduction to machine systems

During this introductory practical class, students visit the university workshop (Figure 1) to explore a range of topics related to machine components and machine and cutting tools. Students examine and interact with components and systems arranged at multiple stations.

3.3. Stress measurements and stress concentration

With this practical work, students recall knowledge of stress and strain, studied in the Strength of Materials course. For this purpose, a basic stand to study the effects of applied forces and moments to beam specimens has been designed and built. The bench allows demonstrating the relationships among forces, moments and support reactions. Buckling phenomena can be observed and measured. By placing a translucent polymer specimen between two polarized sheets using the photo-elastic effect, the student can visualize the distributed nature of loading and the magnification at stress concentrations features (holes, grooves and fillet changes).

3.4. Gears, gear reducers and power transmissions

In this practical work, students examine the integration of an electric motor and a set-up of power transmission components (Figure 2(a)). Learners can observe the working behaviour of real industrial components such as pulleys, sprockets, gear reducers, belt and chain transmissions, couplings, shafts, bearings, brakes and all the components required for the transmission. An electronic speed variator is installed to demonstrate the speed control and the dynamic behaviour of the assembly (a laser tachometer is used). Students are required to perform disassembly and assembly works.

Figure 1. University workshop and availability of lathe components. Source: own elaboration.

(a) (b)

Figure 2. (a) Gear reducers and power transmissions. (b) Cut section model of an automobile gearbox. Source: own elaboration.

A cut section model of an automobile gear box (Figure 2(b)) is available to study its constructive features, placing particular attention to the shifting mechanism. Construction of a kinematical diagram of the gearbox and measurement of the geometrical parameters of the gear wheels are carried out to apply the concepts studied in the lectures of gear transmission theory (kinematics and kinetics) and gear manufacturing. Attention is paid to materials, manufacturing processes and assembly constraints involved in the construction of the observed gearbox. Free-body diagrams that depict the forces acting on gear teeth, for different conditions and gear shafts and bearings must be sketched. In this practical work, students are also indicated to select appropriate gears from catalogues for specific applications.

Students are prompted with questions related to the destination of power transmissions and their components, the shifting process and shifting mechanism design principles, the conceptual criteria involved in their design, their advantages and disadvantages, manufacturing technology, installation, diagnostic, maintenance, and testing.

3.5. Gears reducer test stand

A stand to study the performance of gearboxes under load is available (Figure 3). It is a recirculating torque type test stand with two identical concentric cylindrical gearboxes, one acting as the test box and the other as the slave box. The rig incorporates other three gearboxes, two with two axles each and one with three. The transmission elements are connected back to back and are driven by a small power motor, which has to overcome only the mechanical losses in the mechanical system. The torque is applied by twisting a shaft closing the circuit, by means of a flange type coupling. In this stand, students learn the dynamic behaviour of gear power transmissions and measure power losses; also, other research studies can be performed.

Figure 3. Gear reducer test stand. Source: own elaboration.

3.6. Braking system components

A stand to observe the composition and working principle of a hydraulic driven disk type braking system is available. In this practical work, braking system components, hydraulic master and wheel cylinders, calipers, brake disks and shoes and returning springs can be studied and analysed. The dynamic behaviour of the system and its components can be investigated.

3.7. Cut model of an automotive powertrain

At this station, students investigate the composition of engine mechanisms and their components: crank-slider and cam-follower mechanisms (Figure 4). Students are asked to sketch the free body diagrams of these mechanisms and to describe their design principle and criteria. Kinematic and dynamical models of the mechanisms are explained in detail. Concepts related to lubrication of sliding bearings, valve guides and other contact pairs of the mechanisms are stressed. Again, belt and chain transmissions are reviewed, and particular constructive and technological issues are explained. In this stand, students also observe the operation of the clutch system. Explanations related to the design and operation of the clutches and hydraulic system are given to the students. Students are asked to measure the operational characteristic of a diaphragm spring. In this same stand, learners are challenged to study by their own the types of fits (clearance, transition and interference) and interchangeability properties involved in the mating parts of crank train assembly.

3.8. Cut section model of a hydraulic pump

The activities of this practical work include machine component identification, sketch and study of a hydraulic pump assembly design (Figure 5). Students must sketch and describe the components of the hydraulic assembly (impeller, volute, inlet and discharge piping, shaft seal, shaft, bearings, pump frame, housing seals, baseplate and drive coupling). Attention must be paid to the assembly of the impeller wheel on the shaft and the bearing arrangement.

Figure 4. Cut model of an automotive powertrain. Source: own elaboration.

Figure 5. Cut section model of a hydraulic pump. Source: own elaboration.

3.9. Bearings

In this work, students are introduced to the composition, classification and operation of bearings. The expected life of a bearing should be calculated by the students. Brief explanations of the bearing operation and performance diagnostics are given. Students listen to, with the aid of an electronic stethoscope, bearing noise and vibrations and sense with their hands the temperature of electrical motor bearings; a thermography camera is used in this stand. Students should calculate bearing fatigue life using a web-based life calculator. Samples of worn and damaged bearings and their parts are exposed to the students to explain and recognize the possible types of failure.

3.10. Bolts

In this practical work, students understand the use of bolts as fasteners, investigate the strength properties of different grades of bolts, measure clamping force and assess proper torquing. Preload requirements of the bolted assembly are explained. The identification and the use of bolt types are discussed; bolt grade chart, thread pitch gauges, and torque wrench are used. Bolts with circulating balls are presented. Bolts are purposely over-torqued to observe what happens to the bolt and the pieces being clamped.

3.11. Cylindrical spring

In this work, students measure the deformation-force characteristic of a spring and correlate it with that obtained after measuring spring dimensions (mean and wire diameter, active coils, free and loaded lengths, coils slope). Combined uncertainty of the spring characteristic is discussed. A physical part of a vehicle is exhibited in the laboratory (Fig. 6), where students appreciate the complex composition of wheel suspension, braking system, constant velocity couplings and driver shafts.

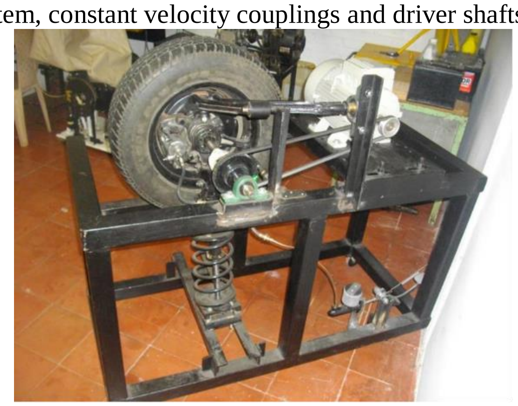


Figure 6. Model of a quarter of vehicle. Source: own elaboration.

4. Small scale projects

Students are faced with the physical creation that is the result of a design process, going backwards through the steps to achieve a greater understanding,, recalling concepts they have studied in previous semesters. The learning outcomes expected from the project include: knowledge and understanding, analysis, problem-solving, innovation, planning and organization, interactive and group skills, product prototype, communication, and presentation. Teams are required to document the product development process from conception to implementation.

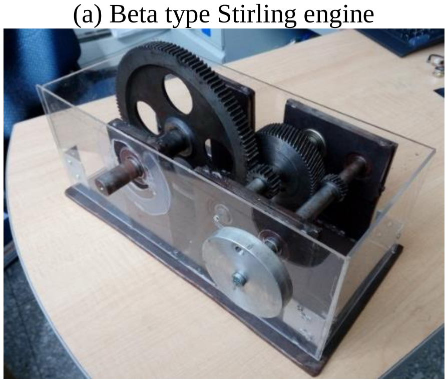
The small-scale design projects are used to establish a relationship between machine design principles and the reality of machine components. The course uses a mixture of common machine and power transmission components with in-class product examples, show-and-tell products and reverse engineering of products.

At the beginning of the course, students are asked to form groups of three or four to work in a series of *six small-scale projects*. Some products developed under minor or small-scale projects include Stirling engine, manual press, four bar mechanism [36], basic manipulator or robot [37], ornithopter, egg carrier, gear speed reducer, spring powered vehicle, hydraulic loader, belt conveyor and a cartonmade chair. The level of difficulty in projects increases along the semester according to course progression. Some of the small-scale projects developed by the students in the Machine Design course are illustrated in Figure 7.

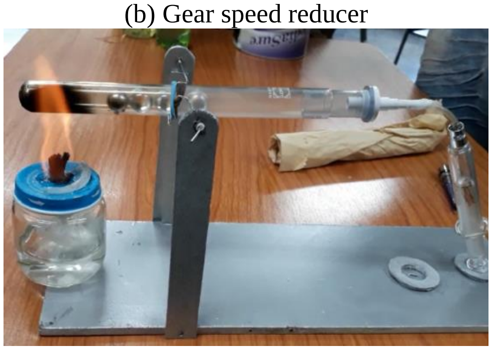
The first *small-scale project* focuses on the concept of design creativity, technical presentation and communication, where the students' groups conceive and put to work a thermo-mechanical device. The first *small-scale project* the students are required to accomplish is the construction of a miniature Stirling engine. This first design experience focuses solely on the design competition through compelling students to apply the basic thermodynamics involved in this device. In the second project, the theory of strength and stiffness is applied to the construction of a drinking straw based chair. The theory and practical application of mechanical springs are carried out in the construction of a torsional spring powered vehicle.

The fourth project is devoted to the construction of a three-stage gearbox for torque reduction. In this *small-scale project*, students are asked to assemble a gearbox after a planned selection of commercial gear wheels and pinions, seals, and bearings. It is recommended to arrange a bolted steel plate based case. There must be a docus on the manufacturability of the shafts and case components. Learners must apply the concepts of geometrical dimensioning and tolerancing of machine components and modules.

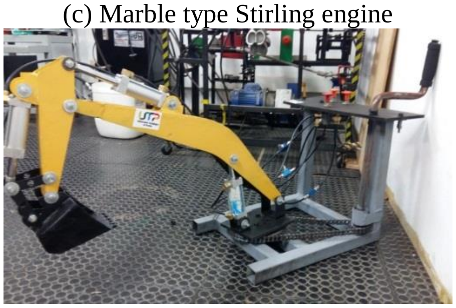
(a) Beta type Stirling engine



(b) Gear speed reducer



(c) Marble type Stirling engine



(d) Hydraulic loader

Figure 7. Samples of small scale projects developed by students in the Machine Design course. Source: own elaboration.

The concept of impact and response of mechanical components to impact loading is dealt with through the construction of a carrier for an egg to be dropped from a certain height. This competition project allows students to explore the different materials available and learn to apply concepts of momentum, impulse, force and energy absorption. The concepts involved in the competition are related to the real problem of collision energy absorption involved in automobile design and the constructive and technological measures to reduce the primary and secondary impacts. The general idea is that students design a container that will allow an egg to safely fall from varying heights without breaking. Often, one of the goals is to use the minimum amount of material. Egg drop projects combine problem-solving skills with basic principles of engineering and physics.

A project intended to disrupt the common sense, as a creative alternative, is the construction of a square wheel to roll smoothly on a road made up of linked inverted catenaries.

5. Main course project

5.1. Characteristics

Understanding that students need concrete experience in which to root the concepts studied in the lectures, the idea of the main course project is to mimic the scenario of a real industrial design project. A concept is embodied while meeting the functional and regulatory requirements. Major design drivers are functionality, performance, safety, technology, resources and cost. This requires the development of project plans and schedules. Sketches, concept drawingss and 3D CAD component and assembly drawings must be made using commercial softwares. The emphasis is placed on creativity and ingenuity as part of the student design project, which also requires oral and written communication. The issues of design for manufacture and design for assembly are reinforced in the project.

The main machine design project relates often to a machine that transforms or transports material or energy (a transport system, a speed reducer, a mechanical press, etc.). Thus, the general layout and geometry of the system are selected after performing a decision tree procedure. The loads are estimated using dynamic simulations for material selection and preliminary sizing of components. In the phase of detail design, all the machine components are calculated taking into account all the interfaces and associated systems.

The main course project serves as the backbone of learning to cover the intended learning outcomes that include acquisition of knowledge through deep learning and development of skills through participation in the learning activities. The project is embedded in the course; it starts in its first week and ends with a built product at the end of the semester. The lecturer asks the student to develop the design of a speed reducer, a transportation crane or transportation system. Detailed procedures are given so that the students conduct their design through several stages from initial concept to the complete solution and a full technical report with the mandatory engineering and manufacturing technological drawings.

5.2. General design procedure

For the main course project, the general design sequence suggested to the students comprises the following activities: specify the working principles related to the project; specify objectives and limitations of the design, including desired life, size, shape and appearance; determine the nature and characteristics of the loads; determine the magnitudes of the loads and the operating conditions; analyse how loads are applied to the elements; sketch the element geometry taking into account constructive and technological issues and the materials selected; consider the treatment condition and the expected properties of the materials chosen; define the appropriate safety factors; perform the preliminary geometrical calculations for all individual parts and design pairs (transmission sets); complete the required stress, stiffness, and stability analyses of all individual parts and design pairs; follow the particular design methodologies for the selection and performance checking of power transmission pairs, couplings and bearings; check all assumptions in the design to ensure that the elements and the entire design object is safe and efficient; specify suitable dimensioning and geometrical tolerances for all dimensions and features, especially conjugate mating surfaces; complete all the required detailed, technological and assembly drawings in accordance with the standards; document the final design with drawings and specifications.

General design procedures have to be presented in spreadsheets. Whenever is possible, simulation and modelling softwares must be used to define the optimum shapes of the parts, making allowance for mass reduction and maintaining the required strength and stiffness. The goal is that students learn the theory of design process in combination with part manufacturing fundamentals, becoming aware of manufacturability.

The students are asked to submit progress reports periodically so that the lecturer can provide feedback to the students before they prepare their final reports. The use of software packages and TICs [38] facilitates repetitive design calculations and parametric studies.

The completed project is presented to an audience of peers. Students are encouraged to present a poster, showing the engineering design process and final product development. The poster is reviewed by the lecturer to correct mistakes and give formative feedback, while the rest of the class formulates questions and takes part in the evaluation.

5.3. Optional “reverse engineering” project

As design fundamentals are presented, students apply the theory of design process to an actual existing product. While holding the object of study in their hands, the students try to understand its functionality, the physical principles involved in its operation, its manufacturability and its assemblability. They dissect and observe it, analyse the functionality and the physical principles behind it, analyse the possible manufacturing methods applied to reach the forms and dimensions, measure them and analyse their interfaces. Redesign involves the process steps of understanding problem statement, specification planning and development, benchmarking, concept generation, product embodiment, design for manufacturing, prototype construction and testing, and production.

5.4. Resources

In order to achieve the course objectives, students have access to facilities for designing, prototyping, and manufacturing products, including CAD/CAM, rapid prototyping, and workshop. Course notes and tutorials for executing the main course project are provided by the lecturer. A list of questions covering the course content is offered for students’ self-evaluation.

Students are encouraged to watch machine design related videos available on YouTube. Electronic mail is used as a useful means of student-student or professor-student communication. Available on the Web technical handbooks, electronic catalogues, design repositories from manufacturers, professional and trade organizations, suppliers of products, and many government agencies play a vital role today to boost the learning process and research in Machine Design subjects. Industry’s websites containing technical data, industrial applications, selection procedures, interactive examples, animation and video are suggested to the students, as a means of highlighting and extending the concepts studied in the lectures.

The Mechanisms and Machine Design Laboratory is equipped with a set of machines and mechanical systems to enhance creative exploration and investigation. The machines and systems include mechanical presses, engines and transmissions, a super mileage type vehicle, a speed reducer test bench for measuring mechanical losses in concentric and conical speed reducers, and various other systems. Some of those systems are shown in Figures 1 to 6. The laboratory is located next to a machine shop where students have access to machining processes (lathes, CNC milling machines, etc.) and to the Materials Testing Laboratory, where students can use testing machines and other equipment.

6. Assessment of student learning

Students are required to present their lecture notes with comments and observations, written and oral reports of small scale projects, and design portfolios. Significant emphasis is placed on documentation and report writing. Brief laboratory reports are required after each practical session in the laboratory.

Critical thinking tasks are assigned to enhance student comprehension and transformation of lecture and laboratory content. A holistic grading scheme is used to evaluate student and team performance. Students are evaluated based on completion of critical thinking tasks and team-oriented activities. Critical thinking tasks represent 20% of the overall student score. Team-oriented activities toward the development of small-scale projects weight 35%. Main course individual project weight 30%. The remaining 15% is completed with laboratory reports.

In the Machine Design course, not only are the teams asked to evaluate and rate each other's work in the final group presentations, but also an anonymous inquiry form judging the contributions of all team members has to be filled out by every student.

7. Conclusions

This paper described a reform of the Machine Design course carried out in the Mechanical Technology Programme at the Technological University of Pereira. As modern pedagogical models involve less lecturing and more active learning,, the new course is taught in such a way that students practice active learning and are more engaged with the course. Learning is made more interactive, and technology and collaborative learning is integrated into the learning experience. Also, students deal with and analyse real components and solve real problems. The educational activities carried out include: (1) hands-on learning in a laboratory environment with real-world hardware, (2) directed and open-ended machine design challenges that promote active learning and force design thinking, and (3) experience working in teams. The small scale and main course projects provide students the opportunity to apply classroom learning in a real environment. It is concluded that the new course has improved learning outcomes, and the pedagogical strategies used are more effective for attaining them.

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