World Transactions on Engineering and Technology Education
Vol.15, No.1, 2017

Hands-on experiences in engineering classes: the need, the implementation and the results

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ABSTRACT: The mission and vision of engineering education should continuously change its focus to satisfy customers' requirements - the industry and the students as future employees. The main issue that needs to be addressed by faculty that teach undergraduate engineering courses is how well the graduate engineers are equipped with the practical skills required by industry. This article describes a systematic approach for introducing practical *hands-on* experiences in engineering courses. The case studies illustrate the implementation, the benefits and the results of this approach designed for student engagement. They will demonstrate the importance of considering both virtual materials and physical materials for hands-on activities, and to implement experiential activities that are employed by practicing engineers.

INTRODUCTION

Engineering education should be an *agile* system whose content should continuously accommodate changes in technology and manufacturing methods to ensure that the graduates will possess the required knowledge, skills and capabilities required by industry. The main goal is to reduce the *competency gap* between engineering graduates and employer's expectations [1]. As succinctly noted by Ragusa and Moore:

> *Engineering companies worldwide seek graduates who can hit the ground running. They want universities to train students, from the first year onward, for engineering practice* [2].

The important role of the engineering laboratory in undergraduate engineering courses has been pointed out by different authors [3-5]. Feisel and Rosa emphasised that:

> *…engineers must have a knowledge of nature that goes beyond mere theory-knowledge that is traditionally gained in educational laboratories* [3].

Student engagement in activities that encourage *learning by doing*, followed by reflection on what was done, will better prepare them for the technology and knowledge based jobs. The term *hands-on, minds-on* learning is used in connection with *student-cantered* or *active learning*, and also *for educational activities that are dynamic, relevant, and applied* [6][7].

Klahr et al suggest that regardless of whether the learner's hands are on physical or virtual materials, one should consider both scenarios as hands-on activities [7]. In this context, virtual materials can be, for example, the objects and animations created using CAD. These virtual materials are designed to act similar to the corresponding physical model. Klahr et al note that:

> *This is an important factor because computers may provide a unique opportunity for* hands-on *activities with virtual materials that avoid many disadvantages of physical hands-on materials* [7].

The findings of Klahr et al [7] confirm what was also observed by Pusca and Northwood [8], that there was no negative effect on the quality of learning using virtual models, even though physical and virtual models differ in visual and tactile information they provide. Clemens and Samara also indicated that *…there is no theoretical or empirical justification* to exclude computer simulations and virtual laboratories from the definition of *hands-on* activities [9]. It should be noted that this approach gives students an opportunity to become motivated and active participants in the learning process by experimenting with different digital tools that are used by practicing engineers. They also can use the acquired skills to make personal decisions regarding future career paths.

As part of hands-on activities in different engineering courses, students create and use models as purposeful representations, i.e. to analyse behaviours, processes or properties. The model formats can be abstract models or concrete models. The abstract models can be iconic: these resemble the system under consideration; for example, a 3D CAD representation of a system. They can be analogic: these behave in the same manner as the system or process under consideration; for example, a process simulation. These abstract models are created using computers and specific computer software, similar to what is used in industry. In graphical design classes, students use augmented reality to visualise virtual models, so that their hands are on virtual materials. Concrete models are created by students for design prototyping and manufacturing projects, and are developed by fusion deposition modeling, using 3D printing [8][10]. In a graphical design course, students use these concrete models to reverse engineer and to create the 3D digital models, so that their hands are on physical materials.

Both these types of hands-on activities contribute to students' engagement and will better prepare engineering graduates to compete in a demanding market. Also, the engineering design process itself requires both types of hands-on experiences - digital and physical - during different development phases of a product or process. It was observed that students respond positively to both of these activities, since they encourage learning through hands-on design [8][9][11]. Another excellent example of combination of hands-on experiences is with architecture students that learn about architecture and processes of construction through design-build projects. The students build these projects with their own hands. It is noted by Anderson:

> *…This type of learning process encourages students to become designers with hands-on experience in making projects as an important extension to imagining and drawing projects. The teaching goal is to develop experience and design imagination harnessing the innate thinking capacity of the hand as well of the mind, in the belief that architectural thinking must emanate from first-hand physical experience and material process of construction craft and technology as well as from theory and abstract learning* [12].

THE OBJECTIVES OF HANDS-ON ACTIVITIES AND THE KNOWLEDGE DOMAINS

The expression *hands-on minds-on* is used to suggest the relationship that exists between the objectives of the activities performed by the students in the engineering laboratories, and the targeted knowledge domains: cognitive, psychomotor and affective (attitude and behaviour) [3][4]. Table 1 summarises the thirteen identified objectives in relation to the knowledge domain [3].

Table 1: Morphological chart for technology based activities [2].

Objective	Knowledge domain		
	Cognitive	Psychomotor	Affective
Instrumentation	●		
Models	●		
Experiment	●		
Data analysis	●		
Design	●		
Learn from failure	●		●
Creativity	●		●
Psychomotor		●	
Safety	●		●
Communication	●		●
Teamwork	●		●
Ethics in laboratory	●		●
Sensory awareness		●	

A note of caution must be made, and this is because even though an activity is hands-on, it does not necessarily mean that it is also minds-on. To qualify for this category, a hands-on activity must be designed to produce long lasting skills and transferable knowledge as part of the required graduate attributes. Students should understand the purpose of the activities and should also be able to formulate the important learnings from their experiences through reflection.

For example, if the students are learning computer-aided design (CAD) and as a hands-on activity they work on the design project for a mechanical valve, their learning experience through this hands-on activity is not the fact that they were able to finalise the project representing the valve, but it is what they learned about CAD, and how to use the CAD software. The graduate attribute targeted through this activity will be the *use of CAD tools*. So, the questions that need to be addressed by the instructors, when considering the implementation of hands-on experiences in relation to learning outcomes are: *What activity is an effective hands-on learning for a specific graduate attribute? What key indicators* *should be considered when analysing if a proposed hands-on activity is designed to achieve the desired graduate attributes?* When involved in hands-on activities, undergraduate students should be able to answer the question *What they learn?*, given in Table 2, as key indicator for the achievement of the desired learning outcomes and the corresponding graduate attributes.

Table 2: Key indicators for an effective hands-on activity.

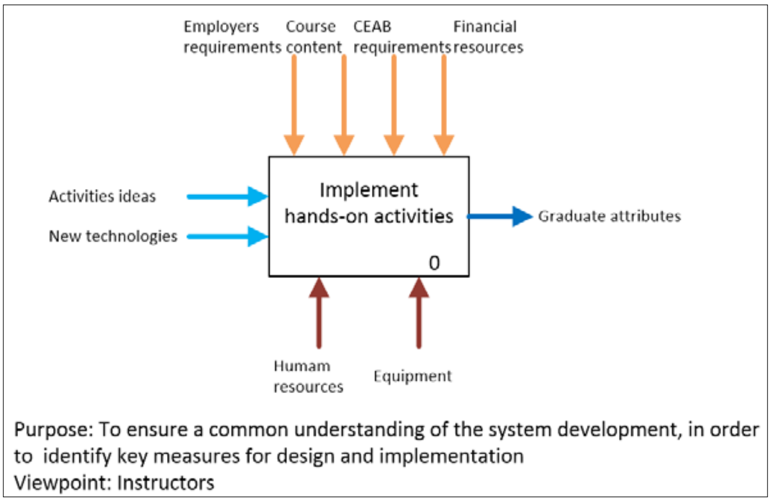
Digital tools	What they learn?	Instructor	Students' competencies	Application in engineering design process
Mobile devices (iOS and Android devices)	Digital sketching Augmented reality	Integration of knowledge: • Sketching • Isometric drawings • Multi-view drawings	Visualisation skills/ spatial abilities Teamwork	Abstraction and synthesis phase
PC computers	CAD packages (CATIA V5) Cloud computing	Integration of knowledge: • Solid modeling • Generative drafting • Animation	Use of engineering tools Graphical communication skills Teamwork	Analysis Implementation
3D printer	Fused deposition modelling	Integration of knowledge: • Prototyping • Additive manufacturing	Use of engineering tools Physical model	Implementation

Each instructor should manifest caution, because although a hands-on activity leads to students' engagement, this may not be sufficient for a successful teaching and learning experience, unless that activity is designed for the achievement of a specific learning outcome and, as a consequence, a desired graduate attribute. As also indicated by other authors, *something* that is to be learned *needs to be better defined through carefully designed learning objectives if the considerable effort devoted to laboratories is to produce a concomitant benefit* [3][4].

DESIGN, IMPLEMENTATION AND ASSESSMENT PROCESS

A systematic approach was used to graphically model the actions, decisions and activities regarding the design, implementation and assessment of hands-on activities in engineering courses [13][14]. This approach includes plans of action as steps of a conceptual design information model, and requires knowledge from design science and cognitive psychology, as well as from practical experience in different domains.

The proposed plans can, then, be adapted in a flexible manner for different engineering courses, in order to achieve specific needs. A graphical model was created to enable communication between all involved, to make sure that the specific needs are met - to implement hands-on activities and also to help decision-making process. The scenario-driven conceptual design information model that was developed from the viewpoint of the instructor's cognition is shown in Figure 1 and Figure 2.



Purpose: To ensure a common understanding of the system development, in order to identify key measures for design and implementation
Viewpoint: Instructors

Figure 1: Phase 1 for conceptual design information model.

The process description starts with a single box as shown in Figure 1, showing the inputs, controls, outputs and mechanisms (ICOMs) for the overall process. This initial diagram also includes the purpose of the project and the viewpoint - in this case the course instructor(s). The box (or node) in this diagram is, then, further decomposed or *zoomed* into a diagram with three boxes as shown in Figure 2.

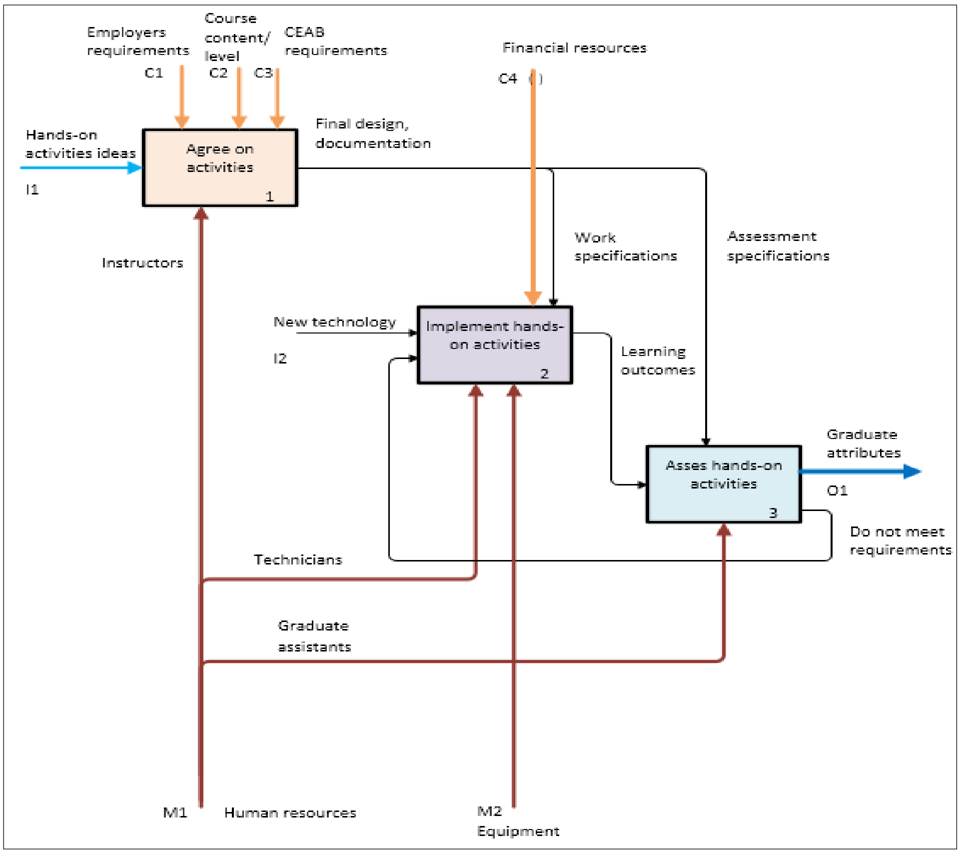


Figure 2: Phase 2 for conceptual design information model.

There could have been up to six boxes, as needed to describe the activities. This hierarchical decomposition may be further repeated for each box in the diagram in Figure 2, and so on, until the process is fully described to enable communication and clear understanding of the specific issues regarding the implementation process for hands-on activities. The ICOMs that were considered in the initial diagram are also identified in Figure 2.

The first task for the course instructor as detailed in Figure 2, is to decide on the hands-on activities that must be developed for a specific course. These type of learning activities are planned only after the identification of learning outcomes and the planning of assessment methods, a *backward design* approach [15-17].

The instructor's main priority at this stage is the students' engagement through hands-on activities that must be planned for specifically designed learning outcomes in order to achieve the desired graduate attribute(s). As a consequence, each hands-on activity is designed to achieve one of the objectives mentioned in Table 1.

This task is constrained by certain controls as identified in Figure 2: employers' requirements, course content/level, and the Canadian Engineering Accreditation Board (CEAB) requirements. The output of this activity is the final design of hands-on activities and related documentation to be used as controls in the implementation phase.

The input for the implementation phase is determined based on the new technology. The implementation mechanism should consider the technicians and the equipment needed for the designed hands-on activities. Financial resources represent the control for the implementation phase. As Chan et al mentioned:

> *…It was understood and granted that laboratories and equipment were part and parcel of effective engineering education. That is in marked contrast with today's fiscal realities of universities operating as corporate entities* [5].

Upon successful implementation of the hands-on activities, the output should be the desired learning outcome as identified in Figure 2. The input for the last phase, assessment of hands-on activities, is represented by the output from the previous phase, the learning outcomes. In this phase, the instructor is interested to *measure* how well the students meet the requirements specified for the learning outcomes as an indirect assessment of graduate attributes.

CASE STUDIES ON HANDS-ON ACTIVITIES IMPLEMENTATION AND IMPLEMENTATION RESULTS

Following the procedures graphically illustrated in Figure 1 and Figure 2, hands-on activities were designed and implemented in two very different undergraduate courses at the University of Windsor: a first-year course in engineering design and a fourth-year course in steel.

Case Study 1: First - Year Engineering Design Course

Table 3 illustrates the hands-on activities as designed for the Engineering Design course. By modernising the teaching and learning process of engineering design through the implementation of technology-based activities, a learner-centred approach to curriculum planning was also achieved [7][18].

Table 3: Graduate attributes, knowledge domain and the overview of technology based activities in Engineering Design course.

Hands-on activities	Equipment	Learning outcome: integration of knowledge	Students' competencies	Laboratory objectives (from Table1)	Knowledge domain
Digital sketching	Mobile devices (iOS and Android devices)	Knowledge: • Sketching • Isometric drawings • Multi-view drawings	Visualisation skills/ spatial abilities Graphical communication skills	Design Models Creativity Communication	Cognitive Cognitive Cognitive/affective Cognitive/affective
Augmented reality	Mobile devices (iOS and Android devices)	Knowledge: • Isometric drawings • Multi-view drawings	Visualisation skills/ spatial abilities	Design Models	Cognitive Cognitive
CAD packages	PC computers	Knowledge: • Solid modelling • Generative drafting • Animation	Use of CAD tools Graphical communication skills Teamwork	Models Communication Teamwork	Cognitive Cognitive/affective Cognitive/affective
Fused deposition modelling	3D printer	Knowledge: • Prototyping • Additive manufacturing	Physical model Teamwork	Models Teamwork	Cognitive Cognitive/affective
Reverse engineering	3D scanner	Knowledge: • Solid modelling	Use of CAD tools	Models Creativity	Cognitive Cognitive/affective

Table 3 gives the cognitive and the affective knowledge domains that are associated with the identified objectives of the instructional laboratory in the engineering design class. The importance of knowledge in the affective domain (behaviour and attitudes) is increasingly being recognised [4], since there is a need for graduates that poses the necessary *skills to work across intellectual, social and cultural boundaries* [19][20], referred to as *holistic engineers*. As a result, the hands on activities considered for this course also respond to the employers' requirements regarding graduates with intellectual, and also social and cultural skills.

In Table 3, both types of hands-on activities are considered: the learner's hands are on physical and virtual materials, so that students learn through hands-on design. This approach is implemented in the context of project-based learning. Students work in design teams to demonstrate their understanding of the entire engineering design process, starting with the need formulation and ending with the implementation phase, consisting in prototyping. In this manner, they have the opportunity to analyse their design solution, reflect, consider further improvements and even learn from failure, if the outcome was not as expected - the same approach used by the design teams in industrial settings. It must be mentioned that this course is designed as a studio-type course, and this allows for a better integration of the lectures and laboratories.

As mentioned by Schadler and Hudson, learning is enhanced by combining lectures and active learning [21]. All hands-on activities indicated in Table 3 require the use of the same digital tools used by practicing engineers to create virtual or physical models. The purpose of implementing the hands-on activities was not only to better serve the instructor's objective to create an engaging and stimulating teaching and learning environment, but also to meet the students' learning needs, allowing them to achieve the desired competencies in course-specific graduate attributes. The students were able to constructively experiment with all these tools, within the time constraints associated with the delivery of the one semester course.

Case Study 2: Fourth - Year Steel Course

Occupying a separate space of the knowledge domain from CAD is the area of mechanical testing. While all engineers are likely to be introduced to the concept of material strength via the tensile test, mechanical property characterisation is a regular part of the curricula associated with civil and mechanical engineering programmes. However, it is common practice to replace the hands-on laboratory with a demonstration for the class; students are, then, provided an idealised stress-strain curve with which to calculate properties, such as yield strength, elastic modulus and elongation.

In a final-year elective in a course on steel, twenty-three students were posed with a seemingly simple task, *Determine the required mechanical properties of a given piece of steel*. The students quickly identified that they had to conduct a tensile test. When pressed to provide the particulars of the testing parameters, sample preparation and reporting requirements, there was silence. Despite previous exposure to tensile testing and mechanical properties, these senior-level students had limited exposure to the actual codes and standards for testing and materials.

Using ASTM Specification E8/E8M Standard Test Methods for Tension Testing of Metallic Materials [22] as the laboratory manual, student teams interpreted the standard and implemented the aspects of tensile testing in Table 4, which maps the testing aspects to their knowledge domains and student competencies.

Table 4. Identification of key aspects of tensile testing.

Testing aspect	Knowledge domain	Student competencies
Select sample type and geometry	Cognitive	Communication (interpretation of code), life-long learning (locating material data)
Prepare and submit a machining/testing request	Affective	Graphical communication, professionalism
Measure sample dimensions and acquire test data	Psychomotor	Engineering tools (callipers, load cell, extensometer)
Determine test parameters	Cognitive	Communication (interpretation of code)
Convert from load-elongation to stress-strain	Cognitive	Use of engineering tools (spreadsheets)
Correct initial data non-linearity	Psychomotor	Visualisation, use of engineering tools (graphs, spreadsheets)
Identify reporting requirements	Cognitive	Communication (interpretation of code)
Calculate required mechanical properties	Cognitive, psychomotor	Use of engineering tools (callipers, spreadsheets)
Teamwork and report preparation	Affective	Communication, teamwork

The key aspects of tensile testing afforded the assessment of numerous student competencies and their associated learning outcomes, which are in turn linked to graduate attributes as defined by CEAB:

- Selection of the appropriate sample geometry required knowledge of the material to be tested: cast, wrought or powder metallurgy; tube or plate. Knowledge of the steel was garnered from ASTM Specification A36 Standard Specification for Carbon Structural Steel [23]. This sort of task links to the graduate attribute of *life-long learning*.
- Use of *engineering tools*, including measuring devices (load cells, callipers, extensometers) and computational methods (data manipulation in spreadsheets), was linked to several key aspects of the testing process. Proper use of callipers and load cell operation/selection had been covered in a previous course. A key learning moment occurred when students, familiar with the analysis of idealised testing curves in their previous courses, struggled with the combination of graphically correcting the initial non-linearity of the test data associated with the sample slipping in the grips and re-zeroing the corrected data in spreadsheet.
- Evidence of successful and unsuccessful interactions with machinists, technologists and other team members were captured on a qualitative basis and are linked to *professionalism*, *teamwork* and *communication*.

Both laboratory sessions and class periods were devoted to this extended learning experience. Students submitted draft reports with full laboratory explanations, despite the reporting requirement of the ASTM Specification E8/E8M [22] for a list of less than ten values. Students recognised the full impact of reporting test results to an industry specification, when the final mark for the laboratory was based on a one-page submission with a simple table of the required values, along with participation marks obtained during the laboratory and in-class sessions.

CONCLUSIONS

In this article, the authors reiterate the need for the hands-on experiences in engineering instructional laboratories. A systematic modelling method was employed to provide the plans of action as steps in the conceptual design information process. These diagrams enable problem areas to be quickly identified and targeted for further improvement. It is shown that a certain level of flexibility is required in the teaching and learning process, even though it must respond to the CEAB requirements, in order to allow for a collaborative endeavour between instructors and industry and, as a consequence, for an effective and meaningful hands-on experience for the students.

The case studies indicate that hands-on activities can foster in the students the development of knowledge and skills in both the cognitive and affective domains: design, creativity, communication, models and team work. They also demonstrate the importance of considering both virtual and physical materials for hands-on activities, which must be designed to produce long-lasting skills. Finally, it must be remembered that it is not only *hands-on* that is required, but also *minds-on*. Just *hands-on* can promote enthusiasm, but *hands-on, minds-on* promotes deeper thinking, which leads to deeper understanding [11].

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