Engineering Design for the E-Waste Recycling Industry – Connecting Industry and Students through Curriculum Projects and Applied Research

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Abstract – Conestoga College (Conestoga) is a post-secondary polytechnic institute located in Ontario. Conestoga has a mandate to provide vocational training to students to make them job-ready. This institute regularly engages with industry partners to bring added value to the education students receive. Many programs, especially engineering degrees, include project-based learning. Project based learning integrates real world challenges directly into curriculum. Over the last ten years, Conestoga, through funding provided by various provincial and federal funding agencies, has engaged industry partners on projects spanning the full breadth of academic programming offered by the institute. One such project focus is research into the recycling of electronic waste (e-waste), which regularly engages engineering students Conestoga's Mechanical Systems Engineering (MSE) and Electronic Systems Engineering (ESE) degrees. Key to this field of research is the design, implementation and testing of automation solutions for e-waste sorting and processing. Conestoga's MSE degree program is a pioneer in bringing industry challenges directly into the engineering classroom to support project-based learning, and in the third year of the four-year degree, a two-semester project course integrates with the curriculum with the explicit goal to provide open-ended engineering design opportunities. In 2019, an opportunity arose for the engineering design and prototype build of a pre-sorting automation system for e-waste recycling. Students are provided rough specifications and requirements by Conestoga's Industrial Research Chair for e-waste recycling along with significant input from e-waste recycling industry partners. Multiple designs are proposed during the first semester, with a final design selected for implementation and testing in the second semester. This curriculum project opportunity enhanced Conestoga's reputation for the development of highly qualified personnel (HQP) for industry, with additional co-op job opportunities in later semesters. The importance of industry / academic collaboration to enhance student attainment of important graduate attributes, including engineering design, is illustrated.

Keywords: work-integrated learning, WIL, highly qualified personnel, HQP, applied research, e-waste recycling, electronics recycling, project-based learning, PBL, curriculum, industry.

1. INTRODUCTION

The concept of project-based learning (PBL) is well established in engineering education, providing opportunities for students to "learn by doing". [1] One of the key opportunities for engineering education is the use of PBL to support the growth of engineering design skills in students, a trait well received by industry when they seek talented graduates. Strong and Striver [2] documented significant problems with traditional engineering education in relation to engineering design, including faculty reluctance promoting industry involvement in the classroom, and the lower value given to industry collaboration in the academic engineering arena.

Engineering degrees at Conestoga have been designed to fully incorporate industry collaboration as part of the experience for engineering students. This integration, through curriculum, capstone and co-op work placements provide ongoing "work-integrated learning" opportunities for Conestoga engineering students. As noted by the Higher Education Quality Council of Ontario (HEQCO), the integration of "curricular learning with workplace experience" is considered key in enhancing educational outcomes in post-secondary institutes. [3]

Conestoga College is a post-secondary polytechnic educational institute located in Ontario. Its overriding mandate is to provide vocational training to students in order to generate "job ready" graduates. Conestoga regularly engages with industry partners, including Program Advisory Committees (PACs) [4] that connect academic program faculty to industry leaders, capstone and curriculum projects, and more recently, industry led applied research. Many programs, especially Conestoga's engineering degrees, incorporate PBL concepts, providing an integration point for real world project challenges directly into curriculum. Applied research through Conestoga's varied centres and institutes showcase a commitment to academic collaboration with industry. [5] This includes the SMART (Smart Manufacturing and Advanced Recycling Technologies) Centre [6], which has been extremely effective in providing high value training opportunities for students through co-op work placements. A key metric for the SMART Centre is the development of highly qualified personnel (HQP) for industry. Research fields relevant to engineering students include supply chain and logistics; food processing technology; safety, wellness and performance; and advanced manufacturing and research into the recycling of electronic waste. This latter pair of research focus areas, supported by Conestoga's SMART Centre, are very suited to industry based collaboration in curriculum and capstone projects.

Conestoga College, through two of its Engineers Canada accredited degrees, Mechanical Systems Engineering (MSE) and Electronic Systems Engineering (ESE), frequently involves industry in curriculum and capstone project courses. MSE, in particular, has been a leader in bringing together industry and academia through curriculum based projects. In the third year of the MSE program design, students are required to complete an eight month engineering design project through two project courses embedded in the program design – MECH73255 (Year 3 Project – A) and MECH73265 (Year 3 Project – B). [7] Through these courses, students work in teams to solve two to three different industry based challenges, vetted by MSE faculty and the academic Chair in the semester prior to the start of the third year of the program. Industry project partners are often recommended to MSE (and ESE) via industry inquiries to the SMART Centre. These project courses provide direct linkage to a significant subset of the 12 graduate attributes (GA) and associated indicators as defined by the Canadian Engineering Accreditation Board (CEAB). [8]

The general MSE curriculum project deployment [9] is summarized in Figure 1. In MECH73255, through steps one through six, student teams are created (GA 6 – Team), and are presented with an industry challenge. These teams either "compete" on common design challenges, or are assigned as sub-teams working co-operatively on a larger design challenge. Teams must identify the key characteristics of the problem at hand and embark on preliminary discussions with industry partners or project sponsors to support a problem analysis and definition exercise (GA 1 – Knowledge Base, 2 – Problem Analysis, 3 - Investigation). Teams use project management tools to document project milestones (GA 5 – Tools, 11 - Economics), develop an analysis of costs and funding sources (GA 11 - Economics) and embark on a preliminary mechanical design to solve the problem using industry standard design tools (GA 4 – Design, 5 – Tools). All students are required to maintain engineering logbooks as part of their project work (GA 8 – Professionalism), develop project schedules and must maintain timesheets to track their effort on their projects (GA 11 – Project Management).

By week four, concept proposals and design reports are presented (GA 6 – Communications), allowing for feedback from faculty and industry partner, and a short iteration phase to pave the way for an agreed upon preliminary design. At this point (step 7), students self-select new functional teams supporting further investigation and design work on the set of industry projects available (step 8).

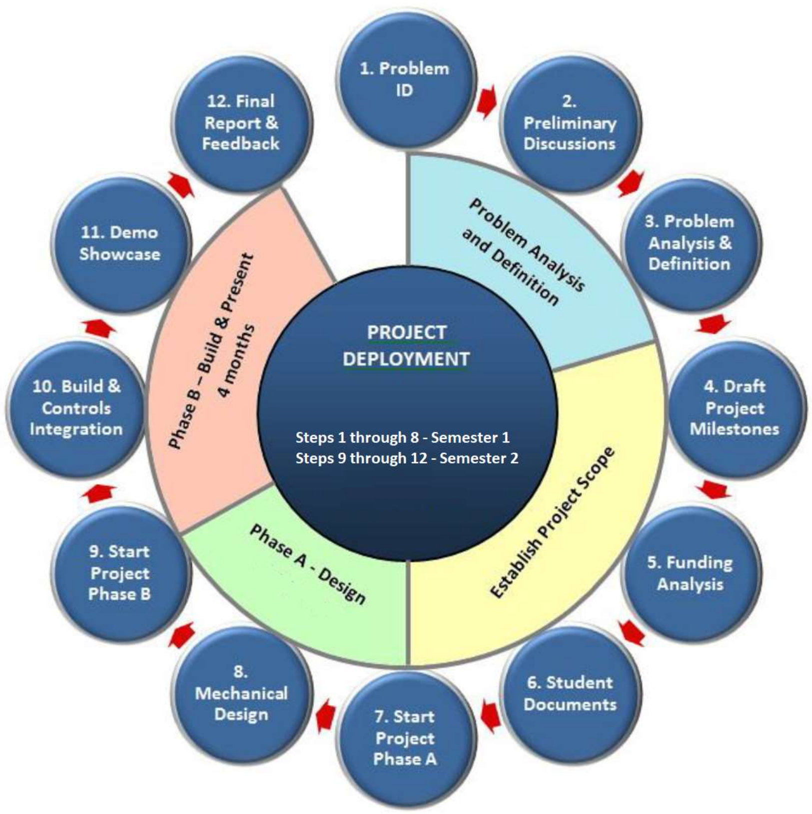

Figure 1: MSE project deployment over two semesters [9]

Figure 1 illustrates how MECH73265 (Phase B, in Semester 2) leverages the engineering design output of MECH73255 (Semester 1) by end of step 8. This allows larger scale teams of students to build and implement a prototype solution based on the approved system design (step 9 and 10), with opportunity for incremental refinement (GA 4 – Design, 5 – Tools, 6 – Team, 8 - Professionalism). Time tracking sheets and project schedules are maintained and updated (GA 11 – Project Management). Lab books continue to be critical to track individual student performance. Students continue their work in functional sub-teams, implementing specific aspects of the design, and then integrate and test into the overall system that meets industry partner specifications. Students take advantage of practical skills developed over the first two years of the program to ensure high quality implementation of the prototype solution (GA 1 – Knowledge Base).

Towards the end of the second course, a public demonstration of the solution (step 11) will be made with industry partners in attendance (GA 6 – Team, 7 - Communications), and in step 12, logbooks as well as a final report are submitted to faculty (and industry partners) for evaluation (GA 7 – Communications, 8 Professionalism).

2. ENGINEERING DESIGN CHALLENGE: E-WASTE RECYCLING

2.1 Selection of Engineering Challenge

Since the mid 2010s, some of the most successful co-op work placement opportunities for MSE and ESE engineering students have been around the applied research work of Dr. Hamid Karbasi, NSERC Industrial Research Chair for Colleges (IRCC) at Conestoga, specializing in advanced recycling technologies. Work placements for students include the design, implementation and testing of automation solutions for electronic waste (e-waste), such as materials sorting, separation and recovery, along with automated product de-manufacturing to assist in material recovery. These work placements offer significant exposure for students to a major problem facing our planet. E-waste is noted by the World Economic Forum in 2019 as the fastest growing solid waste stream in the world [10] and engineers have an ethical and societal duty to find solutions to this growing problem.

To facilitate research in this field, the SMART Centre has constructed a Next Generation Electronic Waste Recovery Pilot Plant within its research facility, as illustrated in Figure 2. Most equipment has been purchased through funding awarded by Canadian Foundation for Innovation (CFI) and Ontario Research Fund (ORF), however, some critical equipment for the pilot plant could not be purchased from external vendors, and had to be designed and implemented in-house to support the research. [11]

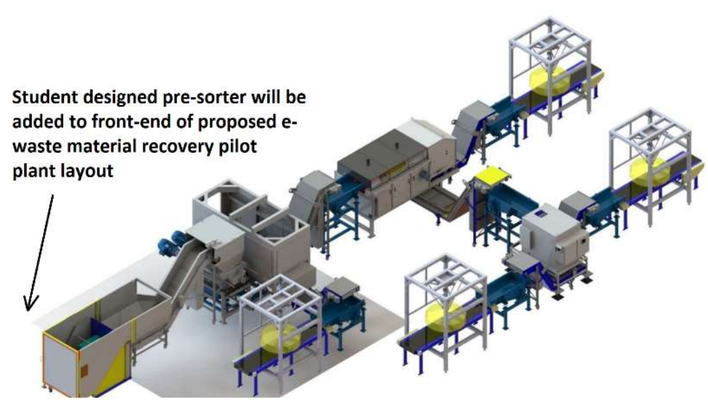

Figure 2: Layout of Next Generation Electronic Waste Recovery Pilot Plant

In 2019, students in the MSE third year design project courses were asked to address a significant industry challenge: design, build and test an automation solution to support the pre-sorting of waste electronic devices that arrive at an electronics recycling facility. This challenge supported ongoing applied research with a key e-waste recycling industry partner who is seeking to dramatically improve throughput on the sorting of incoming waste electronics.

Karbasi and our industry partner provided general requirements and specifications for the pre-sorting system, and Professor Cristian Pop provided project management, mentorship and overall leadership for student teams engaged on this project. The output of these project courses has become key infrastructure for the Pilot Plant, shown in Figure 2 in the lower right section of the Pilot Plant layout.

2.2 Preliminary Design Phase

Key design elements for the pre-sorting system included: a gantry robot to pick and move large waste electronics products, such as printers or laptops; a pair of delta robots to perform pick and place on smaller items, such as cables, mice and batteries. The pre-sorting system required a real time vision system with a machine learning algorithm to control the robotic pick / place operations to effectively sort incoming waste electronics prior to more extensive recycling and material recovery operations.

At the beginning of the winter semester of 2019, the 19 MSE students enrolled in MECH73255 were divided into three sub-teams, each independently developing a conceptual system design for the pre-sorter. These teams were mentored under guidance of Pop, Karbasi and our industry partner.

Further design challenges included a fixed cost for implementation (as budget was pre-set based on CFI/ORF award), and specific real-world performance expectations, as defined by the industry partner.

Table 1: Industry Partner Specifications and Expectations

Specification	Performance Expectations
Handle e-waste of various weight	Payloads of up to 40kg supported
Handle e-waste of various size	Maximum width of e-waste item – 36 inches (dictated by conveyor) Maximum height of e-waste item – 24 inches
Input conveyor speed	500 mm per second, individualizes incoming e-waste items for pre-sorting operation
Output conveyor width	12 inches – to feed sorted e-waste bins
Number of output bins	6
AI enabled machine vision for control	Control robotics to identify e-waste item, and support 30 to 40 pick and place operations per minute to correct output conveyors
Robotics required	Gantry robot (to separate large items), two delta robots for smaller pick and place flexibility

Budget expectations	Large ticket parts (gantry robot, delta robots, work-cell frames, conveyors, control systems, vision hardware, etc.) purchased through fixed amount under CFI grant. Expected return on investment (ROI) such that design / implementation pays for itself in one year.
Safety	Design and build to College health and safety policies and industry regulations

These three sub-teams of students developed preliminary designs and presented their work by week four of the semester. A winning design was selected by Pop and Karbasi. The concept design was updated to merge the best elements of the other two teams, and students were dispersed and asked to self-select into four functional unit design sub-teams, which supported engineering design for: gantry robotics, delta robotics, gripper design and the vision / AI system.

These sub-teams continued on functional design tasks that supported the full-scale design of the pre-sorting system. This process involved our recycling industry partner who provided additional guidance, specifications and other important engineering design requirements to the student teams. At the end of the winter semester, students presented their final functional designs (including mechanical drawings, schematics, bills of material, costing, etc.) and a report of findings to Pop, Karbasi and the industry partner, allowing for additional critique, fine tuning, and approval.

Figure 3: Final prototype of pre-sorter system

2.3 Implementation and Testing Phase

In MECH73265 (second semester of year three), these student functional sub-teams would regroup and begin the implementation of the design into a full-scale, working prototype. Purchase requisitions had to be prepared as part of the MECH73255 outputs, and Conestoga was able to provide purchasing support to obtain necessary components. High ticket items were purchased through an allocation of CFI funding for the Pilot Plant. Smaller items came from an on-campus “parts store” of reusable components established for student projects. Conestoga’s machine shops provided additional fabrication support. Regular checkpoints with our industry partner supported the sub-teams to build-out and test all functional aspects of the design, and the final integration of these units into working prototype of the pre-sorter system.

By mid August 2019, the four sub-teams had implemented a full-scale pre-sorting robotic solution (see Figure 3) now housed at the SMART Centre research facility. The solution occupies approximately 30 square metres of floor space and was designed and implemented with full health and safety requirements as per Conestoga policies and procedures. Since commissioning at end of August 2019, the automation solution continues to be further refined through ongoing applied research project work with our industry partners, which provided four additional co-operative work-term opportunities for MSE students in fall semester of 2019.

2.4 Faculty Oversight and Student Evaluation

Conestoga's third year project courses are structured much like a typical engineering project in industry, and follow a hybrid agile project management approach to ensure that each week, measurable progress is being made, and that students are on track to improving their graduate attribute attainment and meet required learning outcomes of these project courses. Faculty act as high-level project managers, and work with students to underscore the importance of proper planning and meeting strict deadlines on larger scale industry projects.

In the first semester, faculty act as mentors to assist students in their design effort by answering technical questions on specifications, operational characteristics and budget. Each week, during scheduled class time, students will meet with faculty to review design progress to date, which includes evaluation of student time sheets, logbooks and other documentation required for the course. At these meetings, faculty may intervene if a student team is veering off in an unsuitable design direction and help pivot the teams back towards a pathway to success. Evaluation of student progress will include a comprehensive safety quiz, conceptual design report and presentation, project schedules, design analysis report, CAD mechanical design, mechanical drawings and costed bill of materials, purchase requisition forms correctly completed, and logbooks. Students are evaluated on their individual contributions in addition to team contributions.

In the second semester, faculty supervise the build of the solution designed in semester 1. In the case for MECH73265 under the pre-sorter project, faculty and students would travel to the SMART Centre (located off-campus) at scheduled times, and under faculty supervision, each team would fabricate, assemble and test their components as the pre-sorter system came to life, under the project schedules developed in the first semester. Faculty, program technologists and research centre staff including Dr. Karbasi oversaw student health and safety. Students were evaluated on final design reports for: mechanical design, electrical design, PLC programming, assembly and controls integration. Once again, a safety quiz and logbooks were used in evaluation. In the final weeks of the semester, student teams completed a final report for the pre-sorter project and oral presentation to both Dr. Karbasi and our e-waste recycling industry partner. Again, both individual and team based contributions by students were evaluated.

Rubrics for each evaluation are mapped to appropriate graduate attributes. For example, logbooks contributed to growth in GA7 – Professionalism, while costed bills of material and project schedules supported growth in GA11 – Economics and Project Management.

3. OUTCOMES LEADING TO GROWTH IN ATTAINING GRADUATE ATTRIBUTES

3.1 General Outcomes

The opportunity to bring industry design projects directly into the classroom through the pairing of project courses MECH73255 and MECH73265 has proven to be an excellent vehicle to support the growth of graduate attribute mastery for MSE students.

The 2019 cohort of students, through the design and prototype implementation of the pre-sorting system, have been highly instrumental in supporting the goals of the SMART Centre's applied research in recycling solutions for e-waste. The project provided significant problem analysis, investigation and engineering design opportunities for MSE students, to deliver a complex prototype system that includes a gantry robot to sort out heavy e-waste objects (printers, laptops, etc.) and delta-robots equipped with custom grippers to pick up and separate smaller items, such as batteries, cell phones and similar sized items, all controlled through machine vision and AI.

This curriculum project provided significant open-ended engineering design opportunity and excellent HQP training for 19 MSE students who contributed to this project. As noted earlier, the development of HQP is an important metric for the applied research programs of the SMART Centre, and this opportunity further enhances "work-integrated learning" opportunities for this institute's engineering students. HEQCO has documented that concurrent approaches to work-integrated learning (WIL) are one of the effective practices that post-secondary institutions [3] can take to improving the knowledge and skills of students, and this pre-sorter design project provided significant opportunity for concurrent education / practice, and has helped hundreds of MSE graduates become job-ready engineers-in-training in industry, with exceptional coverage of all Engineers Canada graduate attributes.

3.2 Graduate Attribute Attainment

Table 2 provides a snapshot of the graduate attribute development by MSE students in MECH73255 / MECH73265. The MSE program design intentionally incorporates project courses in each semester of the program throughout all eight semesters. This provides a pathway from prescribed projects that develop graduate attributes such as problem analysis, knowledge base, investigation, use of engineering tools and communications, with a shift to open ended projects in year three and four. For Conestoga's evaluation of graduate attribute attainment within its courses, "introductory" implies first time or early stage application of the graduate attribute. For example, for GA9, the MECH73255 / MECH73265 course pair provides an initial opportunity in the MSE curriculum for students to recognize the importance of the impact engineering makes on society and the environment. The term "developed" is used for courses that build upon introductory GA exposure and allows for significant opportunity to develop mastery of the GA. Finally, "applied" is used for courses where students have had significant prior development of a GA, and where are able to leverage their knowledge and skills to a high degree.

As MSE incorporates project-based learning techniques throughout its four-year curriculum, with each semester having a project course, MSE students have had significant opportunity to reach the developed level of graduate attribute attainment by 3rd year of the program. The ability for 3rd year engineering students to successfully design, construct, test, debug and commission a large scale industrial machine build project of this complexity requires significant mastery of many graduate attributes prior to the start of these project courses.

Table 2: Graduate Attribute Attainment (Introductory / Developed / Applied) [12]

Graduate Attribute	Incoming Level	Outgoing Level
1 - Knowledge Base for Engineering	Applied	Applied
2 - Problem Analysis	Developed	Applied
3 – Investigation	Developed	Applied
4 – Design	Developed	Developed
5 - Use of Engineering Tools	Developed	Applied
6 - Individual and Team Work	Applied	Applied
7 - Communications Skills	Applied	Applied
8 – Professionalism	Developed	Applied
9 - Impact of Engineering on Society/Environment	Introductory	Developed
10 - Ethics and Equity	Introductory	Developed
11 - Economics and Project Management	Introductory	Developed
12 - Life Long Learning	Introductory	Introductory

Throughout these project courses, MSE students have the opportunity to incorporate key graduate attributes as they develop engineering designs for industrial challenges, which in turn ensures MSE students to be exceptionally job-ready for their final co-op work term semester. GA 4 – design, continues to be improved in year four, through an eight month capstone project.

Of special note, this e-waste pre-sorting system provided a significant opportunity to develop GA 9 – impact of engineering on society and environment. With e-waste being the fastest growing solid waste streams worldwide, it is imperative that engineers develop solutions to this problem, as noted by Campbell and Wilson. [13]

Campbell and Wilson also state engineers have an ethical duty – “care ethics” – and that the responsibility for the e-waste problem is tied to engineers. Electronics and mechanical engineers design consumable / throw away products, and without solutions for end-of-life repurposing (second life for product), de-manufacturing (to harvest valuable components) and recycling (material recovery), discarded products will continue to pollute landfills around the world. Students, through this project work, developed an authentic awareness of engineering ethics (GA 10), one of the more difficult graduate attributes to map to engineering curricula.

3.3 Comparison to Prior Years

The 2019 rendition of these year three project courses was extremely successful, and as noted, provided some significant exposure to graduate attributes and design opportunities not found in prior years.

In prior years, projects have been oriented specifically around automation solutions for industry partners, with little to no attention paid on how to integrate graduate attributes such as GA9 or GA10. Additionally, the scale of the pre-sorter differed from prior years, in that often, 2 or 3 independent industry projects could be executed simultaneously, and easily be built on-campus within prescribed lab space set aside for 3rd year projects, typically occupying no more than 10 square metres of floor space.

A final difference from past years involved the budget available for parts and components. In past years, projects were often supported by parts available to students through the on-campus parts warehouse, or through modest funding ($20,000) by Ontario Centres of Excellence through their Voucher for Innovation and Productivity (OCE-VIP) that support academic / industry partnerships. The e-waste pilot plant project is supported by a $2M award from Canada Foundation for Innovation (CFI) and Ontario Research Fund (ORF). This provided a substantial budget (> $50,000) for components needed for the pre-sorter project, and required a much higher level of attention to the budgets, bills of material and purchase requisitions than in any other year these courses have run. In addition, the types of components needed (delta robotics, gantry robotics) were far more complex than in prior projects.

As a result, the 2019 run of the third year project course provided an incredible learning opportunity for MSE students, and highlighted a blueprint for future large-scale industry / academic collaborations that support Conestoga's applied research with its industry partners.

4. CONCLUSION

Engineering degree programs throughout Canada continue to improve the opportunities for engineering design and industry integration into curriculum. The third year project courses for Conestoga's MSE degree showcase a unique model of academic / industry collaboration. The opportunity for growth in the mastery of engineering graduate attributes can be achieved through integrated collaboration with industry and work-integrated learning.

Project based learning, in of itself, is an excellent first step, but as has been demonstrated in this paper, bringing relevant, challenging and highly authentic open ended design opportunities from industry directly to students throughout their engineering curriculum can make significant contributions towards mastery of engineering design and other graduate attributes, with graduates ready to solve tomorrow's problems.

Lessons learned in executing the scale and complexity of the industry / academic partnership documented in this paper will help Conestoga improve its approaches to integrating industry engineering design opportunities into engineering program curricula, as well as further improving Conestoga's capacity for applied research.

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