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A Concept Inventory for Knowledge Base Evaluation and Continuous Curriculum Improvement

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Abstract. Students at Polytechnique Montreal have demonstrated the ability to tackle large-scale, complex calculations through their integrative projects. However, high quality engineers must not only master calculations, but the underlying fundamental concepts as well – this level of retention allows them to transfer their knowledge to the new challenges they will face. To ensure this, accreditation criteria for engineering programs in Canada require the evaluation of multiple attributes, the first of which is “a knowledge base for engineering”. While most universities opt to evaluate this attribute through in-class grades, we choose to adapt a pedagogical tool (a concept inventory) to formulate an evaluation of our students. Our students are examined using a subset of questions from more than 800 chemical engineering questions, split into 10 subcategories. Data amassed over four years is presented, showing the impact of various improvements to this tool, as well as its use for instructor feedback and curriculum improvement. Key improvements include question revisions and targeted revisions of muddy concepts in the affected courses.

Keywords: accreditation, attributes, computer tools, feedback, improvement, concept inventory

1. Introduction and context

1.1 Main Issue

The 120-credit Chemical Engineering undergraduate curriculum at Polytechnique Montreal is a 4-year program constructed as a learning program-based approach (Prégent & al., 2009). This program was designed to develop several of students' skills. To ensure that these skills had been gained, a variety of integrative projects have been put in place within four of the program's key courses, which close out each of the four years of schooling.

To develop these skills and put them into action, students must be able to effectively master and combine various elements of their knowledge and know-how (Tardif, 2006). However, experience has shown us that, while in integrative projects aligned with industry, students are able to resolve complex problems that involve a lot of calculation, but have difficulty providing even simple explanations and descriptions of the concepts underlying those calculations. In other words, students are able to resolve problems related to the higher cognitive levels within Bloom's taxonomy (e.g., analysis), but have difficulty with intellectual operations associated with the lower levels (e.g., comprehension) (Anderson & Krathwohl, 2001). This gap in terms of comprehension of basic concepts can lead to transfer-of-learning issues (Perrenoud, 1997).

These basic engineering concepts are reinforced with students throughout their studies. Nonetheless, it was difficult, to the point of being impossible, to determine whether these essential concepts from their schooling were being absorbed in a lasting manner (knowledge retention) (Tardif, 1999). Indeed, while integrative projects are present throughout the curriculum, we have observed that team-based integrative projects lead to the formation of "experts" within the teams. In other words, they split the work according to their preferences and strengths. However, this means that certain students are not afforded the opportunity to reinforce concepts that may have been shaky. To produce engineering graduates with solid foundational knowledge of their profession and who leverage that knowledge to resolve complex, varied problems in real-life situations, it seemed necessary to offer a method of individual evaluation that included the key concepts at the heart of chemical engineering. The results of this evaluation will not only provide students with direct feedback, but will also give professors a means with which to continue to improve their curricula.

1.2 <u>The Canadian Engineering Accreditation Board (CEAB)</u>

In addition to making use of our experience with the issue outlined above, we also must abide by a regulatory framework put in place by the Canadian Engineering Accreditation Board (CEAB). The goal of this Engineers Canada standing committee is to approve Canadian engineering programs grounded in a variety of educational criteria (Engineers Canada, 2016).

One of these accreditation criteria is based on attributes required of graduates and asks that engineering faculties be able to demonstrate that their graduates possess 12 attributes (Table 1).

Table 1: Graduates' attributes (Engineers Canada, 2016)

1. A knowledge base for engineering
2. Problem analysis
3. Investigation
4. Design
5. Use of engineering tools
6. Individual and team work
7. Communication skills
8. Professionalism
9. Impact of engineering on society and the environment
10. Ethics and equity
11. Economics and project management
12. Life-long learning

Each faculty must put in place assessment mechanisms that allow for student learning to be documented. In addition, results obtained from such assessment must allow for the improvement of the educational program (Engineers Canada, 2016).

The first of the 12 attributes (A knowledge base for engineering) covers knowledge and know-how that every engineering student should possess. More specifically, the CEAB defines the number-one attribute as "Demonstrated competence in university level mathematics, natural sciences, engineering fundamentals, and specialized engineering knowledge appropriate to the program'' (Engineers Canada, 2016, p.15). To properly evaluate this attribute, it was necessary to develop a tool that would provide us with clear data on students' abilities.

1.3 Methods for knowledge-base evaluation

To gather data about students' level of knowledge, several strategies are possible. The simplest method, advocated by certain engineering faculties, consists of using the final grades in key courses to make inferences about knowledge acquisition. In our opinion, this approach does not allow for the integration of all the main topics in chemical engineering within a single, unified tool. In addition, the final grade received at the end of such courses represents the results of several assessment mechanisms and not just those directly related to students' knowledge. Evaluation through a course can be a good measure of immediate knowledge uptake, but does not provide information concerning knowledge retention over longer time scales.

Other institutions, such as England's Imperial College, have taken an approach based on yearly examinations (Imperial College London, 2017). This approach creates a situation where, every year, students are faced with a summative evaluation recapping their knowledge, with various mechanisms in place in case of failure. From the perspective of CEAB certification, such an approach is not necessary because the goals of said certification are more related to the continuous improvement of the program, and not strictly to quantitatively evaluating students.

The approach advocated by this article is therefore to offer students a tool which covers all of chemical engineering's main topics, and which empowers them to evaluate their own mastery of those topics in a simple, lasting manner. This tool is a concept inventory. Such tools have been developed previously by other universities (Ngothai & Davis, 2011 ; Csernia & al., 2008)., but not were available in French, nor did they cover the full extent of concepts in a chemical engineering curriculum. Moreover, to the best of our knowledge, none of them have been used as assessments for accreditation or feedback tools for curriculum improvement.

1.4 Objectives

The objectives of this project are to:

- Design a concept inventory that allows for the evaluation of students' knowledge of chemical engineering's main topics
- Document our students' abilities to learn key concepts in chemical engineering
- Improve our educational program by basing ourselves on rigorous analysis of the results

2. Method

2.1 Concept inventory creation

The first step in creating our concept inventory was to determine the main topics associated with chemical engineering. To do so, we consulted a variety of references, which had already dealt with the essential topics in chemical engineering (McCarthy and al., 2005; Bimbenet, 1998; Storck & Grevillot, 1993; Leesley, 1979; Badger & McCabe, 1936), as well as five complete university programs (University of British Columbia, University of Toronto, Université de Sherbrooke, University of Cambridge and Massachusetts Institute of Technology). This review allowed us to focus on certain specific topics that were part of several of the programs: balances, thermodynamics, transfers, reactor concepts, systems engineering, unit operations, and process design. We have compared these topics with the current structure of our bachelor's program and, based on their respective credit weighting in the curriculum, have isolated 10 main topics, along with their constituent sub-categories (Table 2).

Table 2: Main topics in chemical engineering, along with the subcategories tested and the corresponding credit weighting in the Polytechnique Montreal Chemical Engineering curriculum.

Categories	Sub-categories	Number of credits in the curriculum
1. Fluid Mechanics	a. Fluid dynamics b. Pumps and compressors c. Fluid properties d. Static pressure and Archimedes' principle e. Agitation and mixing f. Filtration, sedimentation, decantation, centrifugation and fluidization	5.2
2. Heat Transfer	a. Conduction, convection and radiation b. Heat exchangers c. Condensation and boiling	5.2
3. Separation Processes	a. Psychrometric charts b. Distillation c. Liquid/liquid extraction d. Absorption e. Mass transfer and Fick's law f. Equilibrium g. Humidification	5.2
4. Process Control	a. Unsteady state material and energy balances b. Transfer functions c. State, input and output variables d. Stability e. Controller types f. Control loop synthesis g. Components of a control system	6
5. Thermodynamics	a. Properties of ideal substances b. Ideal and real gases c. Heat and work d. Enthalpy, entropy and free energy e. Phases equilibrium f. Thermodynamic cycles g. Chemical thermodynamics	6
6. Material & Energy Balances	a. Steady-state material balances (basics) b. Degrees of freedom analysis c. Mass balances (with reactions) d. Chemical equilibrium e. Steady-state energy balances (basics) f. Energy balances (with reactions) g. Liquid/vapour equilibrium	5.5
7. Reactor Engineering	a. Isothermal balances b. Equilibrium c. Reaction kinetics d. Non-isothermal balances e. Catalysts f. Conversion g. Reactor design	3
8. Life Sciences	a. Enzymes b. Bioprocess definition c. Microorganisms and cells d. Organic molecules functions e. Physical properties of organic molecules f. Structure of organic molecules g. Isomers and conformation	7
9. Instrumentation & Measurement	a. Operating principles b. Pressure c. Spectroscopy d. Experimental plans e. Measuring instruments installation	4

	f. Laboratory health and safety g. WHMIS symbols	
10. Engineering Tools	a. Energetic efficiency b. Environmental design c. Life-cycle analysis d. Reading diagrams e. Numerical methods f. Programming loops g. Deontology/ethics h. Process safety	8

2.2 Concept inventory structure

The concept inventory is therefore divided into 10 topics representing basic concepts at the heart of the chemical engineering program. For each topic, roughly 80 questions were created and divided into subtopics. For example, the *Material & Energy Balances* topic includes *Steady-State Mass Balances*, *Steady-State Energy Balances* and *Degree of Freedom Analysis* subtopics. This indexation allows for the creation of a test that will have a similar structure for each student.

Here is an example of a typical question, with its indexation (Table 3):

What is the mass of a solution composed of 30 g of water and 1 g of salt?

a. 30 grams
b. 29 grams
c. 31 grams
d. Between 30 and 31 grams

Table 3: Question indexation example

Topic	Material and Energy Balances	X
Subtopic	Steady-State Mass Balance	X
	Steady-State Energy Balance	
	Degree of Freedom Analysis	

It is important to mention that significant effort was devoted to creating clear questions and plausible distractors (answers that were plausible, even if incorrect). For example, for the previous question, several students indicated that the correct answer was “Between 30 and 31 grams”. This distractor seems realistic because during their previous studies, students were exposed to the notion that volume is not additive, but were not particularly exposed to conservation of mass. This is therefore a misconception that is important to detect (Krause & al, 2004).

A total of 95 subtopics and subtopic levels were isolated within the 10 topics. All questions are multiple-choice (choice of answers, matching, rearrangements), allowing for the evaluation of the most essential core concepts within chemical engineering. The goal of the concept inventory is therefore not to evaluate students' abilities to perform complex calculations, resolve long-form problems, or comprehend process intricacies. Within our program, these types of know-how are evaluated using other tools, such as integrative projects.

In addition to indexation, a difficulty level between 1 and 3 was assigned to each question. Every question is therefore codified in the following manner: YY-Z-NN where YY represents the number of the subtopic, Z represents the question's difficulty level, and N represents the question number.

Using that codification system, the questions that make up each test are chosen by the Moodle Quiz interface in a random manner for every category, so that each student will have a different evaluation (consisting of 9 or 10 questions, based on the topic) that is still similar in terms of the difficulty level and concepts covered. This method allows students to repeat their tests several times without receiving the same questions. Thus, students will undergo a different, but equivalent, evaluation each time, to truly ensure their comprehension of the concepts (and not simply their ability to memorize questions).

For each of the tests, it is possible to select the topics and subtopics to be evaluated, and therefore to create personalized tests. Since the number of questions that were created greatly exceeds the number asked during an evaluation, each test is unique.

When a student has completed their test, the software will provide the professor with a result, which can then be used as feedback regarding each topic. In addition, a reading guide has been made available which allows students to review the concepts and address their weaknesses. This approach makes it possible for each student to be aware of their current status regarding their mastery of a variety of topics. They can then independently equip themselves with a plan to address their weaknesses. This ability to take charge of one's own education and take part in continuous learning can be related to evaluation of the CEAB's 12th attribute (Life-long learning), in that it provides them a first opportunity to formulate a personalized study plan (useful later on in their career).

2.3 Implementation

To serve as an assessment tool to evaluate CEAB attribute 1 outcomes, the concept inventory test was implemented in the fourth-year process design class (GCH4125 – *Conception et synthèse des procédés*). Given that this is a mandatory course for all chemical engineering undergraduates, and that its principal objective is to integrate the knowledge acquired over the first three years of the undergraduate curriculum, it was seen as the ideal target for the knowledge test. From the very first lecture, students were informed of the test and its objectives as both a CEAB attribute assessment tool, and as a feedback mechanism for the curriculum. The test would be associated to a 5% mark in the course, attributed as a pass-or-fail grade (0% or 5%) – to obtain full marks, students would be required to successfully answer at least 50% of the questions in each category. The test was conducted in a reserved computer room, under exam conditions (no material permitted, strict invigilation), over a 110-minute period. Using the MoodleQuiz system, each category had a 15-minute time limit imposed, to ensure that students would access a maximum number of subtests. Students were provided with an instruction sheet for login, which also contained a select few formulae and data for the "fluid mechanics" subtest (including friction factors, adimensional number definitions, as well as the Bernouilli and Hagen-Poiseuille equations), as this subtest was constructed with the expectation that students would have access to this written documentation.

While students were given the list of categories on which they would be quizzed, they were explicitly instructed not to study beforehand, such as to provide baseline feedback to the department concerning which concepts were well-assimilated. Since the objective of the assessment is not to penalize students, repeat tests took place every two weeks until the end of the term – students would be permitted to redo the subtests where they had been unable to obtain a 50% grade (they received a 15-minute time allowance per failed subtest). To help them succeed in these do-overs, as mentioned previously, they were provided with a list of recommended readings from their previous classes, targeted per subtest and per subcategory. For example, if the student had failed the "reaction engineering" subtest, and knew that they had trouble with catalysis, they were referred to Chapter 10 in Fogler's *Elements of Chemical Reactor Engineering* to brush up on the key concepts. This also has incidental impact on CEAB's attribute #12 "life-long learning", by encouraging students to improve upon themselves in areas of difficulty. Some minor procedural changes were applied over the first few years of the test, discussed in section 3.

Beyond its use as a summative assessment tool in the fourth year, the "Material and Energy Balances" subtest from the concept inventory has also been implemented at other points in the undergraduate and graduate curriculum. Namely, this subtest is used as a formative assessment tool in the first-year introduction to process analysis class (GCH1140 – *Analyse des procédés*). It is also implemented as a qualifying test for several chemical engineering graduate classes (where course requirements are not strictly enforced by the registrar's office), particularly for students enrolled in the "Diploma of Higher Specialized Studies" graduate certificate program (*DESS – Diplôme d'études supérieures spécialisées*) who may not have engineering backgrounds.

3. Results and discussion

3.1 Continuous improvement

Following its first year in the field, the concept inventory underwent its first refit. Using the test data collected, each individual question that had statistically amassed a success rate less than 50% over the first year was reassessed, using the following questions:

I. Is the question poorly formulated, too long or unclear?
II. Is the question pertinent? Does it evaluate understanding or rely on memorization?
III. Was the correct answer improperly programmed into the Moodle Quiz interface?

For example, one question in the “Fluid Mechanics” subtest was originally formulated as follows:

> *A compressible fluid exits a tank through a converging nozzle. Which of the following statements correctly describes the flow regime in the nozzle?*
>
> *a) The flow will be supersonic if the outlet pressure is smaller than the critical pressure of the system;*
> *b) The outlet pressure has no impact on gas flow;*
> ***c) The flow cannot be supersonic in a converging nozzle**;*
> *d) The flow will be supersonic if the outlet pressure is greater than the critical pressure of the system.*

This question had a success rate of 30% during the first year of assessment. While this original formulation does focus on a fluid mechanics concept (flow through a nozzle), it was deemed necessary to reformulate it, based on reasons (I) and (II): the answer relies on the student knowing off the top of their head the details of supersonic fluid flow. While we expect students should be able to understand this, we do not require such concepts to be memorized. The question was reformulated as follows:

> *Which of the following statements pertaining to flow through a nozzle is true?*
>
> *a) For there to be flow, the pressure in the nozzle outlet must be higher than the pressure at the inlet;*
> *b) Flow at the nozzle throat can be supersonic (Ma > 1);*
> ***c) For the flow in the diverging section of the nozzle to be supersonic (Ma > 1), flow at the nozzle throat must be sonic (Ma = 1);***
> *d) The shape of the nozzle can alter the mass rate of the fluid flowing from the inlet to the outlet.*

This new formulation, while testing for the same concept, can be worked through by the student during the test if they do not specifically recall details of supersonic flow. Moreover, a schematic of a nozzle identifying its various sections now accompanies the question. The number of questions that were revised during this process following the first year of testing are classified per subtest in Table 4. Out of 831 questions, 285 were examined and 48 were revised. Further, it is interesting to note that, through the random processing of questions by the Moodle Quiz interface, 8 questions were never assigned. Through the revision process, additional questions and variants were added, bringing the total number of questions up to 990 from year 2 onwards.

Table 4: Questions revised per subtest after year 1

Subtest	Number of questions with a success rate <50%	Number of questions with a success rate of 0%	Number of questions revised
Fluid Mechanics	23	3	11
Heat Transfer	23	2	4
Separation Processes	25	2	3

Process Control	20	1	2
Thermodynamics	39	4	2
Material & Energy Balances	42	2	18
Reactor Engineering	29	1	3
Life Sciences	23	3	5
Instrumentation & Measurement	21	2	0
Engineering Tools	40	6	0
TOTAL	**285**	**26**	**48**

Further changes to the implementation procedure were applied following this revision process. As of Year 2, statistics for each test (including do-overs) were presented in class, allowing students to understand what themes are problematic for their classmates and better situate themselves within the group. These statistics were always presented to the undergraduate curriculum committee, but had been withheld from the students during Year 1. At the students' request, time management during the tests was altered from Year 2 onwards: rather than limit each test with a 15-minute timers, students could manage their time as they saw fit. Noticing a drop off in student participation after multiple failed tests, and because the material being tested was deemed a necessary baseline of concepts in chemical engineering, it was decided to increase the students' stake in the test starting on Year 3: successful completion of the course (GCH4125) became contingent upon success in the concept inventory test (50% in all subtests, mandatory do-overs every two weeks to facilitate student success).

3.2 Progression over four years and impact of feedback

The effect of the grading scheme change becomes apparent when considering the evolution of failed subtests (Figure 1). Despite comparable class sizes ($N_{year\ 1} = 49$, $N_{year\ 4} = 47$, separate cohorts), the students appear to take the exercise significantly more seriously on Year 4: on their 2nd attempt (i.e. the first time they actively study for the test), the number of students who pass goes from 9 to 21. Moreover, we see that students persist in taking the test until they pass, reaching a 7th attempt for one student in Year 4, whereas the highest number of attempts in Year 1 was 5.

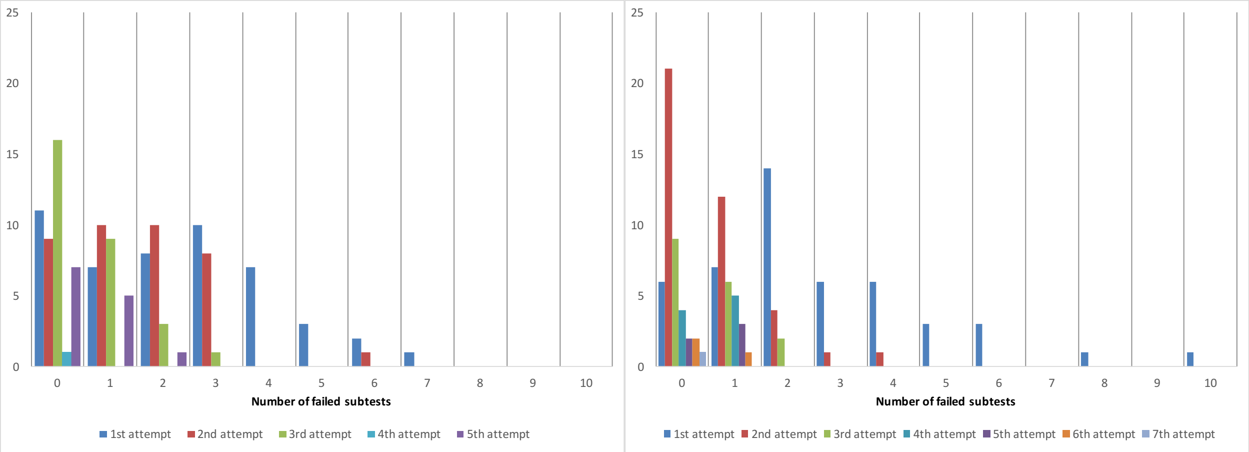

Figure 1: Number of failed subtests per attempt on Year 1 (left, *N* = 49) vs Year 4 (right, *N* = 47). The increases in the total number of attempts and success on the 2nd attempt show that students take the activity more seriously in Year 4.

This improvement is also visualized through the distribution of failed subtests across categories (Figure 2). The percent values indicated in Figure 2 represent the ratio between the number of failures at the 2nd and 1st attempt – in Year 1, the average ratio is 45%, while in Year 4 this decreases to 17%, further illustrating the marked improvement on the second (and subsequent) attempt. The distribution per concept category also brings to light the impact of the revision process initiated after Year 1 (these were observed as early as Year 2, data not reported), as well as feedback provided to some professors. For example, students succeeded in the "Material & Energy Balance" category to a far greater extent in Year 4: 14 failures on the 1st attempt, compared to 22 in Year 1. The contrast is even more drastic for subsequent attempts. The reader will recall that the "Material & Energy Balances" category was the most revised after Year 1 (Table 4).

"Reaction Engineering" also showed a great deal of improvement over the 4-year span, namely as a result of using the concept inventory assessment tool to provide feedback to the professors involved in teaching this subject. After amassing 2 years of data concerning failures in this category, the undergraduate curriculum committee met with the professor in question (who had himself contributed many of the questions used in this category). During Year 3, the professor conducted a 2-hour workshop in his class, during which he presented a selection of five frequently-failed questions from the concept inventory. He reviewed each question carefully with the students and helped them to clarify muddy concepts, and adapt how he taught these concepts in subsequent years. Incidentally, this workshop also had a positive outcome for his final exam. When these students reached GCH4125 (Year 4), they had only 14 failures in the 1st attempt (compared to 21 in Year 1), 3 failures on the 2nd attempt and none afterwards. This improvement is almost entirely attributed to the feedback given by the undergraduate curriculum committee, as the "Reaction Engineering" category was one of the least revised after Year 1 (Table 4).

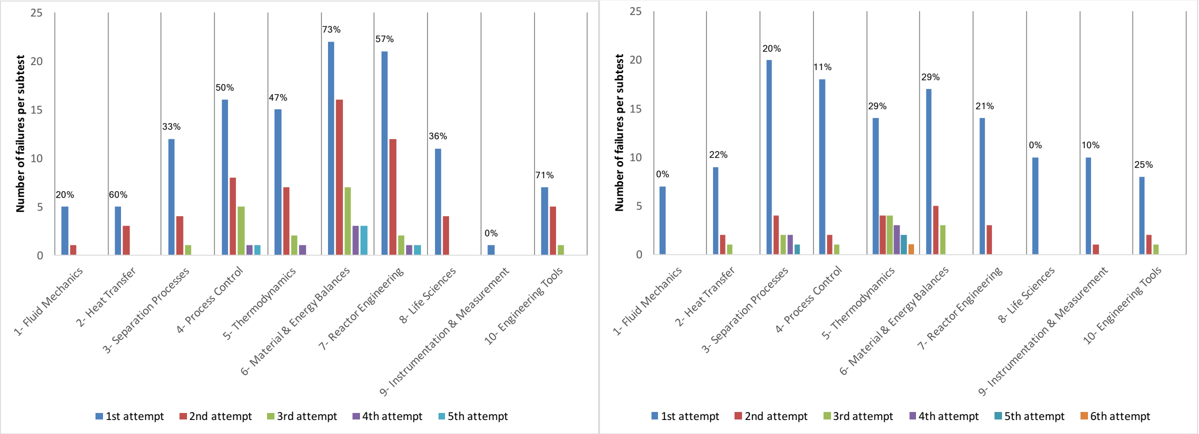

Figure 2: Distribution of failures by subtest in Year 1 (left) and Year 4 (right). The percent values above the data represent the ratio between the number of failures at the second and first attempt, further illustrating the improvement in Year 4.

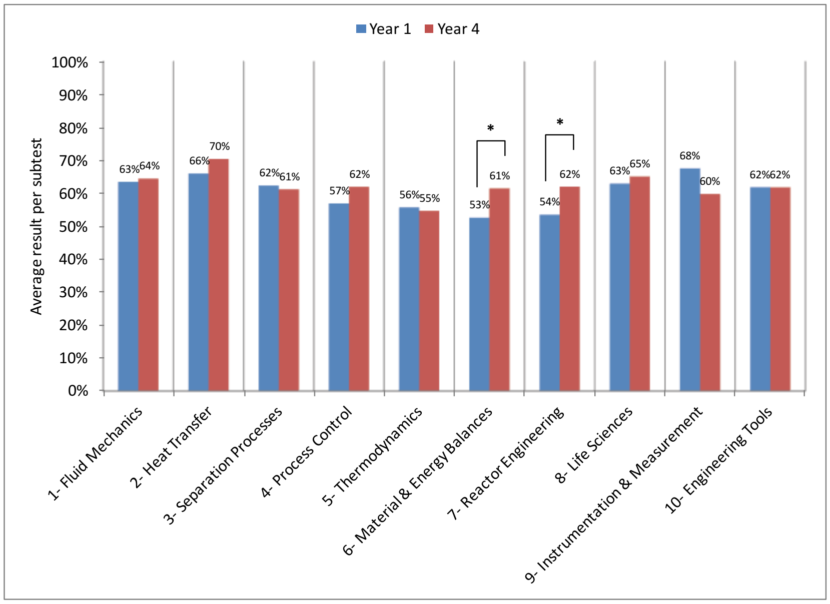

Figure 3: Comparison of average test results per subtest on the 1^{st} attempt. All subtests show identical or improved results, with only Material & Energy Balances and Reactor Engineering showing statistically significant improvement (highlighted with a *)

The noted improvements in performance for “Material & Energy Balances” and “Reactor Engineering” are further apparent when comparing the average test results from the 1^{st} attempt between Year 1 and Year 4 (Figure 3) – the average result increases by 8% in both cases. In fact, revisions, curriculum improvement through feedback and increased attention to the test by students (course requirement) have shown dividends in nearly all categories – the average result on the 1^{st} attempt has either remained roughly identical or improved, though improvement is only statistically significant for Material & Energy Balances (p-value = 0.05) and Reactor Engineering (p-value = 0.03).

The only exception is “Instrumentation & Measurement”, a subtest that was plagued with technical difficulties during the first test on Year 4 (images would not load properly).

4. Conclusions

A concept inventory assessment tool was designed and constructed to allow for the evaluation of students’ knowledge of a full range of chemical engineering topics, spread across 10 subcategories. This tool has allowed us to document our students’ abilities to learn key concepts in chemical engineering, and data analysis from 4 years’ worth of testing has been used for feedback to instructors in order to improve our educational program. This new tool is now used as a summative assessment for the first of 12 graduate attributes defined by the Canadian Engineering Accreditation Board (A knowledge base for engineering) – an accreditation process centered around continuous curriculum improvement. Beyond the undergraduate curriculum, this tool is finding applications in introductory and graduate classes. The next step will be to use the tool as a formative assessment (not strictly summative in fourth year) over the first three years of the undergraduate curriculum, such as to form the basis of a longitudinal study that would show our students’ progression.

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