

Time and Cost Analysis of Implementing a Mechatronic Experience in an Engineering Technology Course

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Raman enjoys teaching and has taught courses including freshmen engineering (mechanics and computer programming – to classes ranging in size from 20 to 500+), sophomore and junior level courses on mass and energy balance applications to biological systems engineering, numerical methods, electric power and electronics for technology students, senior design, as well as a long-standing residential/online graduate course on the fundamentals of biorenewable resources and technology. He believes well trained, curious, thoughtful people are crucial to a university's research effort, and similarly to the function and survival of society. For this reason, the overarching goal of his teaching is to impart the core content needed by the students, and to do so while encouraging inquisition and higher levels of thought. He has secured competitive funds to support his teaching efforts – from university, industry, and federal sources – and for his efforts has received departmental, college, and national teaching honors including the Farrall Young Educator Award given by the American Society of Agricultural Engineers, and an invitation to participate in the National Academy of Engineering's 2013 Frontiers in Engineering Education Conference.

Raman chairs the ABE Engineering Curriculum Committee and in that role oversaw the successful 2012 ABET accreditation visit for both the Agricultural Engineering (AE) and Biological Systems Engineering (BSE) degree programs. Upon arriving at ISU in 2006, he led the development of the BSE program, and this program now enrolls ~100 students. Raman also runs multiple summer research internship programs through his roles in CBiRC and CenUSA. In his role as Pyrone Testbed Champion for CBiRC, Raman and his students have developed early-stage technoeconomic models of bioprocessing systems. His graduate students have gone on to faculty positions at Purdue and the University of Georgia, and to engineering leadership positions at companies including Cargill, Nestle, and Merck.

Time and Cost Analysis of Implementing a Mechatronic Experience in Engineering Technology

Abstract

Using an observational methodology, we studied the time and cost associated with developing and piloting a mechatronic experience in a first-year undergraduate engineering technology course. Our exploratory study included a sample size of 48 students across two sections of an existing course and analyzed the categories of capital, support staff, and instructor time and cost. Our capital purchases totaled ~\$5,000, or ~\$104 per student. Analyzing the capital verse capacity (class size) of our study, we found it to follow the chemical process industry's common 0.6 economies of scale model. In contrast, support staff and instructor time and cost were not proportional to class capacity, but were primarily driven by the discrete stepped requirement of one teaching assistant per 50 students. Finally, setting our capital, support staff, and instructor costs as a function of class size, we projected a ~\$4,000 per semester total cost, with a step size of ~\$450 at each additional increment of 50 students.

Background

Both project-based learning (PjBL) and problem-based learning (PrBL) pedagogies have been found to be impactful in science, technology, engineering, and mathematics (STEM) curricula. Matthew and Hughes¹ indicated these strategies “produce broad-based, flexible graduates who can think integratively, solve problems and be life-long learners”. This is closely aligned with Papert and Harel's² concept of constructionism, in which students play an active role in learning by creating a tangible artifact during a curricular activity. According to Verner and Ahlgren³, mechatronic-centric experiences are a viable example of these frameworks in engineering and technology education, where the artifact is a mechanical and electrical hardware system joined and often controlled by a computer software system. When we consider the rise of PjBL, PrBL, and mechatronic experiences in STEM, Yadav and colleagues⁴ offer tempered insights. They have called for further research to better understand how generalizable the effects of these pedagogies are to a broad range of educational scenarios. Furthermore, while conducting a recent systematic review, we found limited evidence of research discussing the economic impacts of mechatronic experiences. The predominant findings in the literature^{3, 5-10} have focused on the effects that these experiences can have on student learning and engagement, with limited discussion quantifying the time and cost associated with implementing these experiences. These findings motivated our research presented in this paper.

Purpose

The purpose of our research was to understand the expenditures required for mechatronic experiences. To this end, we developed and piloted a study at a large mid-west university to address the question, “What is the time and cost associated with implementing a mechatronic experience in a first-year engineering and technology course?” Answering this question, we presented an itemized bill of material (BOM) highlighting the most costly components as well as the overall capital cost as a function of the class size. Furthermore, we analyzed personnel time

and cost to better understand the per-phase and per-position expenditures, the most significant tasks, the one-time and reoccurring costs, and the per semester total costs as a function of class size.

Methods

We used an observational methodology to study time and cost associated with developing and piloting our study to 48 students across two sections of an existing undergraduate course. We fit our data to a quantitative model to describe the capital and personnel cost trends as a function of the number of students. We only collected data that were above and beyond the course's traditional baseline requirements. These additional data were collected from personnel timesheets and capital purchase orders during our project's *development* (March 2015 to October 2015) and *pilot* (October 2015 to January 2016) phases. We used these phase designations based on the recommendation of the Institute of Education Science's *Common Guidelines for Educational Research and Development*¹¹.

The data collected from our development and pilot phases were analyzed by the categories of capital, support staff, and instructor time and cost. Our capital data were based on a sample size of 48, which used a two by four student teaming structure that allowed one robot platform to be shared by two students. Furthermore, we assumed a maximum deployment period of 4 years with two extra robot platforms and no breakage or replacement. Time and associated costs for support staff and instructor were based on hourly rates using national salary averages¹², an average 2,080-hour work year, and our university's standard hourly multiplier of 1.7. We assumed one instructor for all course sections, and one teaching assistant per 50 students enrolled. The projections at the end of our Results and Analyses section are based on these assumptions.

- *Support staff*: time and cost incurred by lab technician staff (\$38/hour), administrative support staff (\$34/hour), and teaching assistants (\$17/hour)
- *Instructor*: time and cost incurred by instructor (\$61/hour)

Setting

In this section we illustrate the setting in which we conducted our observational study. This is intended to support appropriate generalization of our findings.

Course

Our mechatronic experience was implemented in a first-year engineering technology course titled *Solving Technology Problems*. This course was a requirement for all students within our department's two engineering technology majors, as well as a requirement or elective for other technology majors from across our campus. Two sections were offered each semester, each capped at 48 students. A traditional engineering problem solving methodology was taught using application-based activities and projects from agricultural and manufacturing scenarios.

Student Learning Objectives

Three student learning outcomes were used in our course as *enduring understandings*, which followed Wiggins and McTighe's¹³ *Understanding by Design* methodology. All of these outcomes were assessed throughout the mechatronic experience and are defined as follows,

- Effective problem solving involves clearly communicated data-driven solutions using technical tools and quantitative methods.
- Effective problem solving is cyclical and involves the fundamental inter-related phases of Define, Identify, Determine, Produce, Analyze, and Communicate.
- The fundamental problem solving method can be applied to all aspects of technology.

Mechatronic Experience

The tangible artifact used in our mechatronic experience was the computer controlled mobile robot in Figure 1. This experience was developed for and piloted to 48 students in its first semester of deployment. The culminating challenge for this experience required student teams to collectively create and integrate original software code to control the mechanical and electrical hardware components of a mobile robot to complete a predefined task (e.g. follow a line through a course). In the four weeks preceding this final challenge, teams of two students were individually responsible to complete five topic-centric activities. These activities were intended to shape student's software (code) and hardware (motor and sensor) integration skills. This two by four teaming structure, as illustrated by Table 1, was intended to allow students to build their feelings of self-efficacy in successfully completing the easier activities (teams of two) in preparation for completing the harder final challenge task (teams of four). Furthermore, a problem-based pedagogy was used to reinforce the content of each activity and link it to the challenge tasks. In all this, our design and administration was significantly informed by the methods and lessons learned from others^{3, 5-10}.

Table 1. Semester schedule of mechatronic experience activities and challenge tasks.

Semester Week	Week Topic/Task	Experience Requirement	Teaming Structure
8	Variables, Data Types	Complete 5 Activities	2 students/team
9	Arithmetic, Constants		
9	Flow Control, Switch Case, Break		
10	Digital & Analog I/O, Time		
11	Motor & Sensor Function		
12	Challenge Task Development	Complete 1 Challenge Tasks	4 students/team
13	Challenge Task Development & Testing		
14	Challenge Task Testing		
15	Challenge Task Completion/Presentation		

Results and Analyses

Table 2 describes the time and cost findings, by category and phase, from our study. Equipped with these high-level results, we performed the analyses in the following sections.

Table 2. Time and cost associated to each category and phase of the mechatronic experience.

Phase	Category					Totals	
	Capital	Support Staff		Instructor			
Development	\$4,949	8.0	\$280	158.0	\$9,685	166.0	\$14,914
Pilot		50.0	\$894	25.0	\$1,532	75.0	\$2,427
Totals	\$4,949	58.0 hrs	\$1,174	183.0 hrs	\$11,218	241.0 hrs	\$17,341

Capital Cost

Table 3 illustrates the equipment needs from our mechatronic experience. This BOM, which included only items above and beyond our course's baseline capital needs, totaled close to \$5,000 or \$104 per student. We divided this equipment into the primary subsections of robot platform and support equipment. This informed our discussion concerning department verse student purchased equipment. For detailed specifications and technical resources related to each of the BOM items, please refer to the links provided in Table 3.

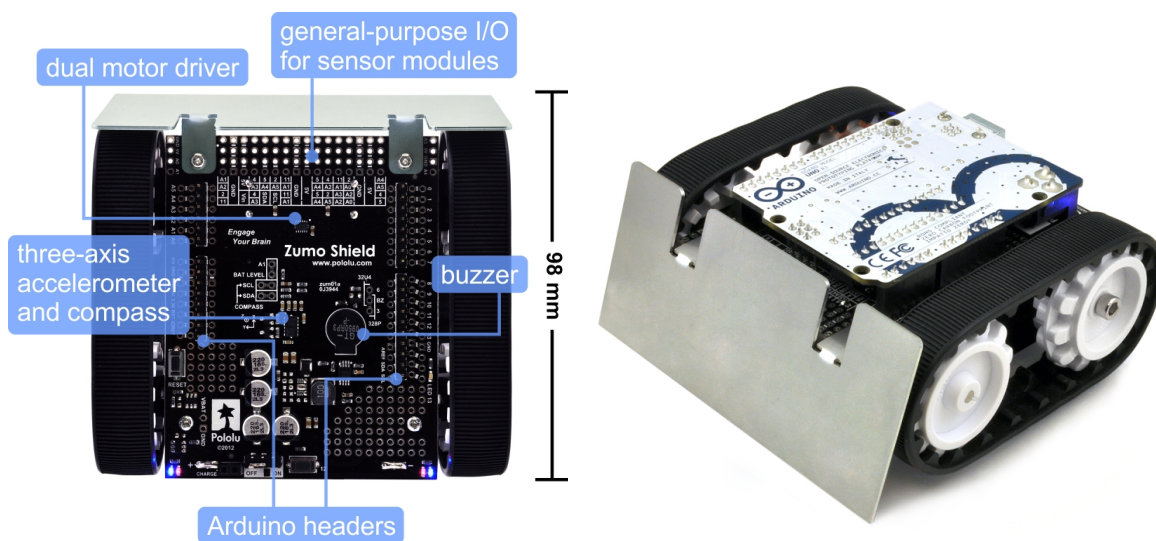


Figure 1. ZUMO robot chassis and Arduino UNO microcontroller used in the mechatronic experience¹⁴.

The majority of our capital cost was attributed to the robot platform items, which were required of students to complete the mechatronic experience. The most notable of these items was the ZUMO robot by Pololu. This compact and robust chassis (see Figure 1) was equipped with two 75:1 horsepower metal geared motors, integrated motor drive circuits, three-axis accelerometer/compass, piezo-electric buzzer, status light emitting diodes (LEDs), a user pushbutton, and an infrared reflectance sensor array for high contrast sensing. The most advantageous aspect of this chassis was the wide range of microcontroller boards it accepted. While we selected the well-known Arduino UNO Rev3 microcontroller, many others are suitable, including all Pololu's A-Star 32U4 family and other similar form factor third-party offerings. One board and cable were given to each individual student, while one chassis was shared across teams of two students.

The most costly support equipment item was the rolling storage case by Lista. This five-drawer, tool chest style case was instrumental in organizing our equipment. While some may question

the necessity of this item, the benefit of mobility that it afforded to the deployment of the experience justified its significant cost.

Table 3. Mechatronic experience BOM.

Qty	Part Number	Description	Manufacturer	Reference Link	Unit	Total	Sub*
26	3124	ZUMO Robot (Assembled w/ Motors)	Pololu	http://goo.gl/YuqdwM	\$90	\$2,340	RP
50	DEV-11021	Arduino UNO Rev3 Microcontroller	Arduino	http://goo.gl/BN6pCh	\$25	\$1,250	RP
50	CAB-00512	USB Programming Cable, 6'	N/A	http://goo.gl/uUyfw2	\$3	\$150	RP
1	N/A	12" Extension Cord	Topzone	http://goo.gl/n9fgRF	\$9	\$9	SE
1	50281	3-Outlet Tap	GE	http://goo.gl/BCElsw	\$6	\$6	SE
1	N/A	6-Outlet Surge Protector, 2pk	AmazonBasics	http://goo.gl/DumuKJ	\$12	\$12	SE
7	N/A	AA Recharge Batt., 2100mAh, 16 pc	Rayovac	http://goo.gl/57EmB5	\$30	\$210	SE
13	N/A	8xAA Battery Charger, NiMH	Rayovac	http://goo.gl/j9o2RD	\$10	\$130	SE
1	900803	Foam Board, 10pk	Elmer's	http://goo.gl/gmIBvV	\$55	\$55	SE
1	NW0600-0402N-M	Rolling Storage Case	Lista	N/A	\$787	\$787	SE
						Total	\$4,949

*RP = Robot Platform; SE = Support Equipment

Figure 2 is a Pareto analysis of the capital cost for each BOM item. This graph aligns with the Pareto model, illustrating that 20% of the items (ZUMO robot chassis and Arduino UNO board) accounted for ~80% of the overall cost. This was not surprising, as these were the most technically advanced items required. Therefore, the selection of a chassis and board are of primary importance when developing and budgeting a mechatronic experience.

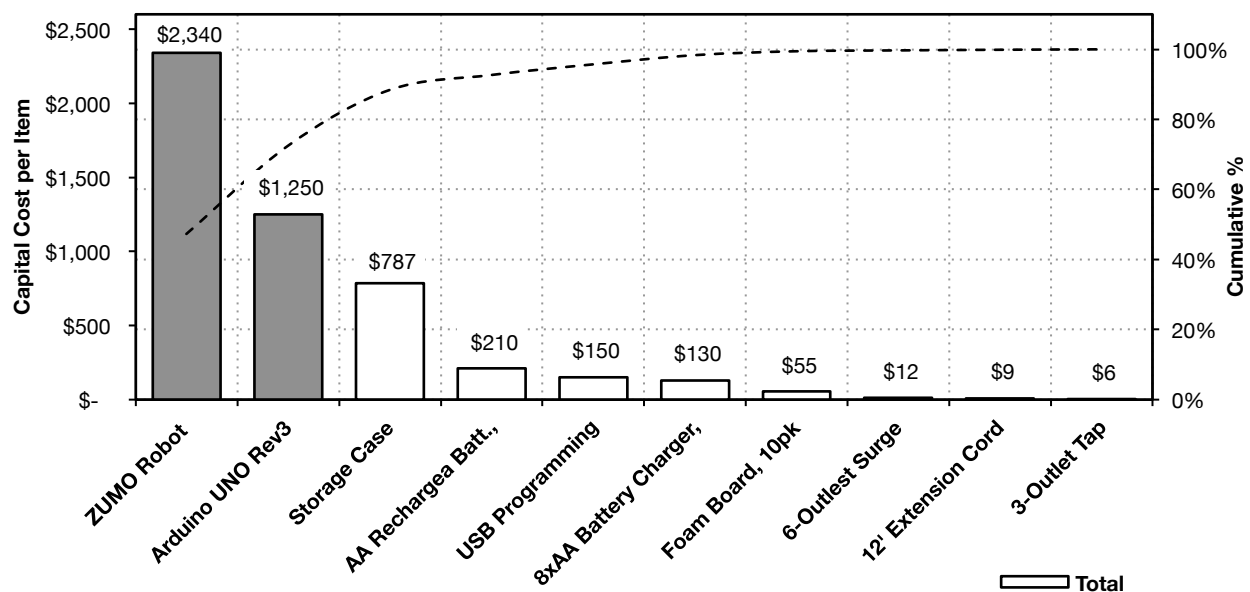


Figure 2. Pareto analysis of BOM capital cost per item.

Figure 3 illustrates a projection of the total capital cost (left y-axis) per the number of students per semester (x-axis). Interestingly, the trend line of projected total capital cost ($y = 1835.9x^{0.644}$; $R^2 = 0.989$) followed a 0.6 power rule. This rule of thumb, grounded in observations of the common economies of scale for capital equipment verse capacity in the chemical process industry, suggests that the scale factor will be on the order of 0.6¹⁵. Based on our scale factor result of 0.644, we postulate that the 0.6 power rule can be applied to the capital costs of our mechatronic experience. From the perspective of departmental purchased equipment, this would support an argument for large class enrollments. Similar to the inherent upper physical limits of chemical process equipment (i.e. maximum allowable size) that disrupt the 0.6 rule, the number of students enrolled in a class may have an upper limit (i.e. due to safety issues). Based on our experience, we advocate for a maximum of 50 students per section. Therefore, the solution to this upper limitation problem would be to add sections in discrete steps when the course's enrollment reaches multiples of 50 students.

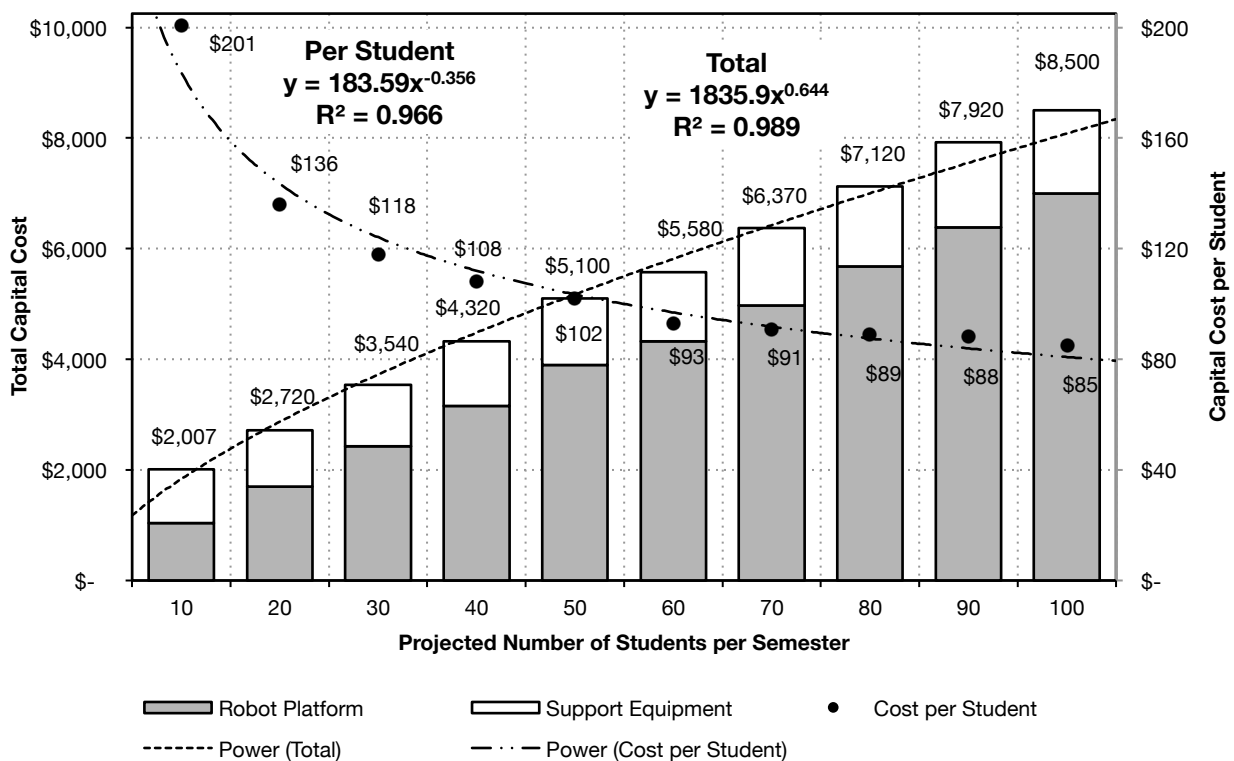


Figure 3. Total (right y-axis) and per-student (left y-axis) capital costs over the number of students per semester (based on one robot platform per two students).

Figure 3 also illustrates our projection of the per-student capital cost (right y-axis) per the number of students per semester (x-axis). This curve ($y = 183.59x^{-0.356}$; $R^2 = 0.966$), which is the inverse of the total capital cost curve, is helpful when considering the student purchased equipment perspective. In this scenario, our results again adhered to the 0.6 power rule model, indicating that per-student capital costs will decrease proportionally as the number of students increase. Therefore, regardless of a student-centric or department-centric perspective of capital

purchases, our findings again followed the 0.6 economy of scale model that endorses proportionally decreasing capital costs as class sizes are increased.

Personnel Time and Cost

It is important to state that the 0.6 power rule model did not apply to our support staff and instructor personnel time and cost. This is to be expected, as labor costs are not proportional to capacity scale¹⁶. Table 4 describes the personnel time and associated cost for each phase, position, and category. The total time and cost to develop and pilot our experience was ~240 hours at ~\$12,000. Of this, ~180 hours (~\$11,000) were assignable to the instructor. Furthermore, ~86% of this time was spent during the development phase (~160 hours, ~\$9,600), which is not surprising as this phase of a project is often dominated by high salary personnel positions. Analyzing our pilot phase time, the picture is meaningfully different. While support staff time (50 hours) was twice that of instructor (25 hours), support staff cost (~\$900) was nearly half that of instructor (~\$1,500). This is again credited to higher salaries required for instructors verse other personnel positions. Lastly, Table 4 illustrates our development time (~170 hours) and cost (~\$10,000) were nearly twice and four times as high, respectively, as pilot time (75 hours) and cost (~\$2,500). This analysis reveals that 1) the majority of the personnel time and cost for the mechatronic experience were attributed to the instructor during the development phase, while 2) the majority of the pilot phase time came from the teaching assistant.

Table 4. Personnel time and cost by category, phase, and position (totals and subtotals in bold).

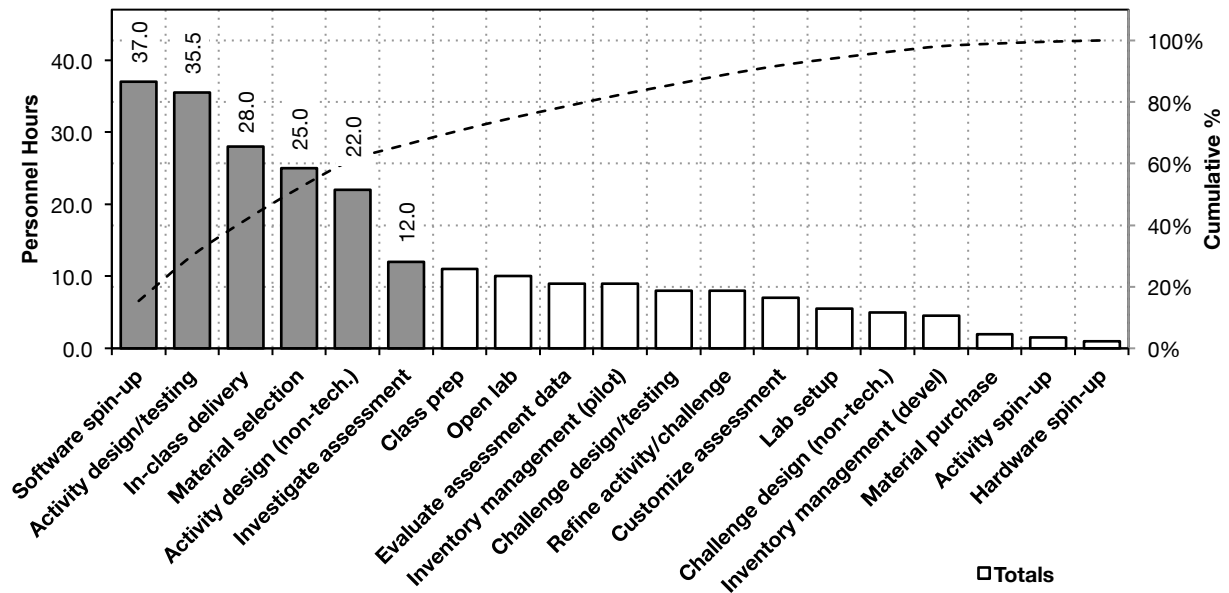
Phase	Position	Category				Totals	
		Support Staff		Instructor			
Development		8.0	\$280	158.0	\$9,685	166.0	\$9,965
	Admin Support Staff	2.0	\$69			2.0	\$69
	Instructor	1.5	\$92	158.0	\$9,685	159.5	\$9,777
	Lab Tech Staff	2.0	\$75			2.0	\$75
	Teaching Assistant	2.5	\$45			2.5	\$45
Pilot		50.0	\$894	25.0	\$1,532	75.0	\$2,427
	Instructor			25.0	\$1,532	25.0	\$1,532
	Teaching Assistant	50.0	\$894			50.0	\$894
Totals		58.0 hrs	\$1,174	183.0 hrs	\$11,218	241.0 hrs	\$12,392

The Pareto charts in Figure 4 highlight the most significant tasks performed across all phases, categories, and positions of our study. Graph a) demonstrates that the time spent on six of the tasks (*software spin-up* through *investigate assessment instrument*) comprised ~75% of the total effort. Furthermore, the instructor performed all but one of these tasks during the development phase, while a teaching assistant performed the other (*in-class delivery*) during the pilot phase. In contrast, graph b) illustrates *in-class delivery* was not significant from a cost perspective. This finding reveals that, while the teaching assistant's time for *in-class delivery* was significant, the associated cost was not.

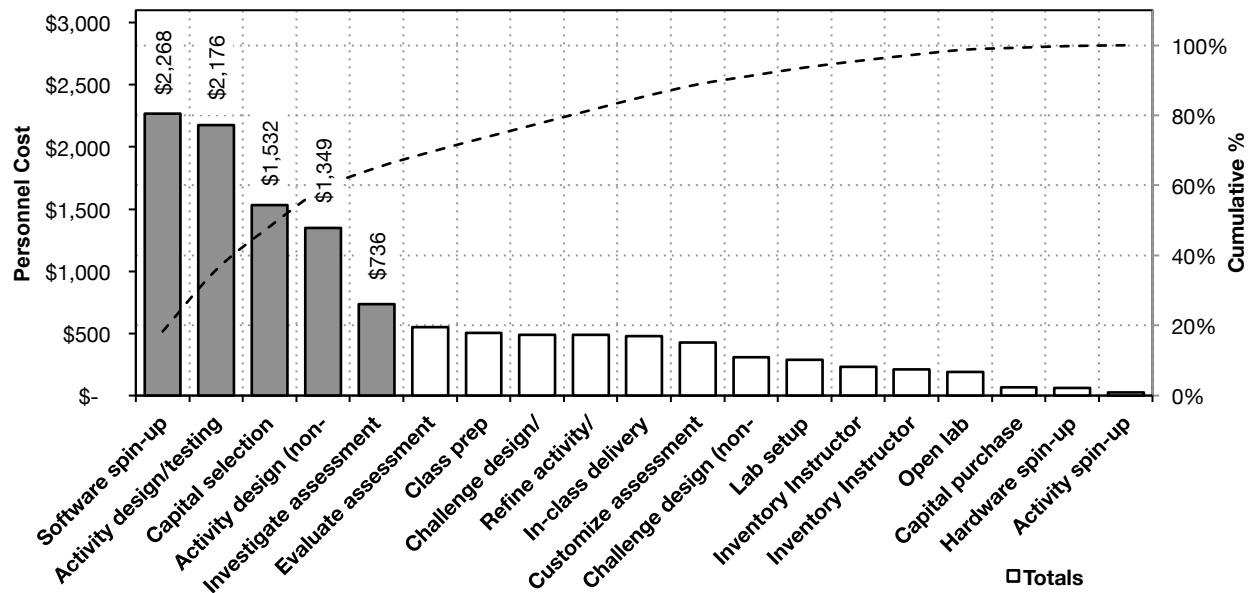
Combined Capital and Personnel Cost

We conclude our results with Figure 5, which is a projection of combined capital and personnel costs per the number of students in a semester. This graph assumes one-time and reoccurring costs calculated over a four-year deployment period, as described in Table 5. As previously stated, the capital cost will increase at a scale factor of 0.644 up to 50 students. Beyond this, capital remains constant due to the assumption that section sizes are capped at 50 students and equipment is shared across sections. Furthermore, the instructor's costs remain constant across

all class sizes because our study analyzed only the time and cost above and beyond the baseline levels of an existing course.



a)



b)

Figure 4. Pareto analyses of personnel a) time and b) cost per task.

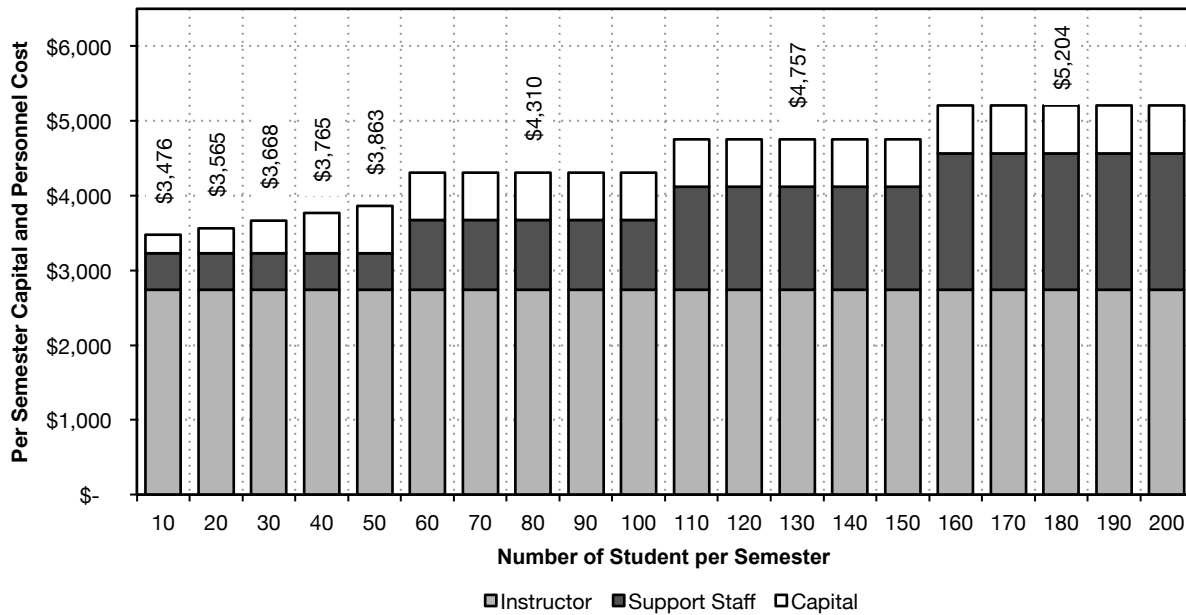


Figure 5. Projected capital and personnel costs over the number of students per semester (assuming a four year deployment period and a 50:1 student to teaching assistant ratio).

The most significant aspect of Figure 5 is the stepped effect that the projected per semester capital and personnel costs exhibit. At class sizes of 60 to 100 this cost was projected to stabilize at ~\$4,000. This should remain constant until enrollment numbers exceed 50 additional students. At these break points, the cost is expected to increase at a constant step size of ~\$450. This is a direct product of the number of teaching assistants required for different class capacities. This also illustrates the non-proportional relationship between personnel and class size. Furthermore, the stepped profile of our results illustrates key class size break points that can be exploited to maximize capital and personnel cost expenditures when implementing a mechatronic experience.

Table 5. Per semester costs by phase and category (assuming a four year deployment period).

Phase	Category	Subtotals	Totals	Iteration
Development	Capital	\$619	\$1,864	One-time
	Instructor	\$1,211		
	Support Staff	\$35		
Pilot	Instructor	\$1,532	\$2,427	Re-occurring
	Support Staff*	\$894		

*This cost is projected to be duplicated for each additional 50 students enrolled a semester.

Conclusion

We found the total time and cost of our mechatronic experience deployment to be ~240 hours at ~\$17,000. Based on a sample size of 48 students, we reported a total capital cost of ~\$5,000 (~\$104 per student). Furthermore, development phase time (~170 hours) and cost (~\$10,000) were nearly twice and four times as high, respectively, as pilot phase time (75 hours) and cost (~\$2,500). However, more interesting than these descriptive findings were the following,

- Capital costs had a scale factor of 0.644 per class size capacity, fitting the 0.6 economies of scale model and were irrespective of a student-centric or department-centric perspective on capital purchases.
- The majority of capital costs were linked to the robot platform (e.g. ZUMO robot chassis and Arduino UNO board), which should be of first importance when budgeting and developing a mechatronic experience.
- Personnel time and costs were not proportional to class capacity, but were primarily driven by the discrete stepped requirement of one teaching assistant per 50 students.
- The majority of the personnel time and cost were attributed to the instructor during the development phase, while the majority of the pilot phase time came from the teaching assistant.
- Combined capital and personnel costs per semester as a function of class size were projected to be ~\$4,000 (at 60 to 100 students), with a step size of ~\$450 at each additional increment of 50 students. This profile illustrated key class size break points that can be significant when implementing mechatronic experiences.

With these findings, we hope to lay a foundation for clear and informative empirical data concerning the time and cost required for implementing mechatronic experiences in undergraduate courses. Furthermore, additional research is needed to extend our model to include steady-state time and cost. We intend to conduct this future work over subsequent semesters.

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