International Journal of Engineering Education Vol. 35, No. 1(A), pp. 209–220, 2019
Printed in Great Britain
0949-149X/91 $3.00+0.00
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Incremental Cost Analysis of First-Year Course Innovations*

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Many experiences in engineering education boast positive gains to students' learning and achievement. However, current literature is less clear on the economic costs associated with these efforts, or methods for performing said analyses. To address this gap, we proposed a structured approach to analyzing the incremental costs associated with an experience in engineering education. This method was modeled after those found in medicine and early childhood education. We illustrated our methodology using marginal (above baseline) time and cost ingredients that were collected during the *development*, *pilot*, and *steady-state* phases of a mechatronic experience in a first-year undergraduate engineering technology course. Specifically, our method included descriptive analysis, Pareto analysis, and cost per capacity estimate analysis, the latter of which has received limited discussion in current cost analysis literature. The purpose of our illustrated explanation was to provide a clear method for incremental cost analyses of experiences in engineering education. We found that the *development*, *pilot*, and *steady-state* phases cost just over $17.1k (~$12.4k for personnel and ~$4.7k for equipment), based on 2015 US$ and an enrollment capacity of 121 students. Cost vs. capacity scaled at a factor of –0.64 ($y = 3{,}121x^{-0.64}$, $R^2 = 0.99$), which was within the 95% interval for personnel and capital commonly observed in the chemical processing industry. Based on a four-year operational life and a range of 20–400 students per year, we estimated per seat total costs to range from roughly $70–$470, with our mechatronic experience averaging just under $150 per seat. Notably, the *development* phase cost, as well as the robot chassis and microcontroller capital cost were the primary cost terms of this intervention.

Keywords: incremental cost analysis; cost-effectiveness analysis; cost ingredients

1. Introduction

In a recent systematic review [1], it was found that current literature surrounding the use of mechatronic experiences in technology and engineering education have primarily focused on the effects of student learning, motivation, and engagement. These authors defined *mechatronic experiences* as projects or activities that require students to design and/or develop a machine that performed a defined function or task [2]. This inherently requires the integration of mechanical and electrical hardware systems with computer software systems and are a tangible example of project-based learning (PjBL) and problem-based learning (PbBL), which both garner much acceptance in science, technology, engineering, and mathematics (STEM) education. Matthew and Hughes [3, p. 239] advocate that these pedagogies, and related experiences, enable "students to perform at the cognitive levels which academics intuitively wish them to", while Yadav et al. [4] call for further research to better understand how generalizable the effects of PjBL, PbBL, and related experiences are to a broad range of educational scenarios. However, limited discussion in the mechatronic experience and broader engineering education literature has included analyses of the incremental costs incurred by these types of interventions. While some studies proposed educational frameworks for these interventions [5] and others analyzed the economics of these systems apart from an educational application [6], none focused specifically on the incremental costs incurred. This is alarming, as it is increasingly important to quantify the monetary impact of these pedagogies given the drop in educational funding in recent years (e.g., 2015 United States funding dropped nearly 30% compared to fiscal year 2000 [7]).

1.1 Background

While a well-established literature for cost analysis of general education and health interventions does exist [8, 9], we are unaware of literature that has applied these methods to mechatronic experiences specifically, or even engineering education broadly. To find the first substantial publication on cost analyses in education, one must start with Levin's [10] *Cost-Effectiveness Analysis in Evaluation Research* and Rothenberg's [11] *Cost-Benefit Analysis: A Methodological Exposition*, both printed in the *Handbook of Evaluation Research*. Levin followed this initial publication with a book titled *Cost-Effectiveness: A Primer* [12], in which he outlined three distinct approaches to costing: *cost-benefit analysis* (i.e., unit cost per unit benefit),

* Accepted 25 September 2018.

cost-effectiveness analysis (i.e., unit cost per unit effect), and *cost-utility analysis* (i.e., unit cost per unit utility). Six years later, Barnett and Escobar [13] published a very succinct review of select studies using either cost-benefit analysis (CBA) or cost-effectiveness analysis (CEA) for elementary education interventions. In all these examples, they stressed the need for longitudinal studies that capture the effects, costs, and benefits to the target population *and* society. Twelve years later, Levin and McEwan published a revised edition under the title *Cost-Effectiveness Analysis: Methods and Applications* [9] in which they added a fourth approach: cost-feasibility analysis, which is intended to allow for a quick evaluation of competing alternatives against a budget. More recently, Scharff, McDowell, and Medeiros [14] and van der Velde et al., [15] have presented similar methods for evaluating the cost-effectiveness and/or cost-benefits of educational interventions in food science and medical education, respectively. Furthermore, McEwan [16] provided an in-depth framework for conducting CEA in education and medicine, among other cost analysis approaches. He defines CEA as the incremental cost ($) per unit of incremental effect, allowing for an incremental cost per incremental unit effect ratio (CER) or incremental effect per incremental unit cost ratio (ECR) to be calculated. From this ratio, a clear relationship between costs and effects of an experience can be realized (e.g., test scores increased by y points per x monetary units expended, or expending x monetary units will increase test scores by y points).

Focusing on incremental costs, Levin [12], Levin and McEwan [9], and McEwan [16] gave specific "ingredient" inputs that can be quantified and compared against either incremental effect, benefit, or utility. These inputs include: *personnel* (e.g., full-time, part-time, consultant, volunteer, etc. human resources), *facilities* (e.g., classrooms, offices, storage space, land, etc.), *equipment and materials* (e.g., furniture, scientific apparatus, instructional equipment, experience material, computer equipment, commercial tests, etc.), *client inputs* (e.g., books, uniforms, transportation, etc. required of clients), and *other inputs* (e.g., all other miscellaneous costs that do not readily fit into other ingredient categories). These ingredients are evaluated over a single or multi-year span using either market prices (if their market value is known) or shadow prices (if their market value is unknown). Furthermore, Levin and McEwan [9] stipulate, that for situations where monetary expenditures are made across multiple years, future and past "nominal" costs should be adjusted for inflation to a predefined present "real" cost (i.e., the market value of a predefined product or service in year one will change in value in year two, due to inflation). For situations where expenses are made in future years, Levin and McEwan [9] stipulate that these costs should be discounted to account for the time value of money (i.e., the opportunity cost of spending a dollar now is higher than if that dollar is spent in the future). Therefore, the ingredients function as opportunity costs and offer a direct mechanism for quantifying the economics of an experience [17].

The intent of these costing approaches is to provide policy makers and institutional leaders the evidence based data they need to make informed decisions on where to invest scarce resources. These approaches provide a mechanism for evaluating the monetary effectiveness of an educational intervention. While examples of simplistic equipment centric *ex post* descriptive costs of interventions (i.e., analyses based on actual costs) have been published [18–20], there appears to be a severe lack of publications discussing *ex ante* analyses of costs per capacity (i.e., analyses based on forecasted costs per intervention size), or formally conducted cost-effectiveness analyses. This appears to be a significant gap in the literature and was a primary motivator for conducting our study.

2. Purpose

A defined method for analyzing incremental costs and scalability of an educational experience is not novel. However, the use of these analyses in engineering education, and more specifically the use of *ex post* analysis that goes beyond simply equipment costs to include personnel costs during the development, pilot, and steady-state phase of the intervention, as well as *ex ante* scalability analysis of cost per capacity, do appear to be innovative. Therefore, we proposed a method and exemplary application example for conducting *ex post* and *ex ante* analyses that included descriptive analysis (*ex post*), Pareto analysis (*ex post*), and cost per capacity analysis (*ex ante*). Fig. 1 illustrates how each of these analyses were used to characterize the incremental costs associated with our example educational intervention. Salient data used in our analyses are also included in this figure.

We hope the characterization of *ex post* cost and *ex ante* scalability of implementing an educational intervention will provide educators with a straightforward method for assessing costs. It is also intended that this paper supports the formation of more rigorous cost-effectiveness analyses in engineering education. In the Methods and Materials section, we discuss methodological details of *ex post* cost results for personnel and capital ingredients across the *development*, *pilot*, and *steady-state*

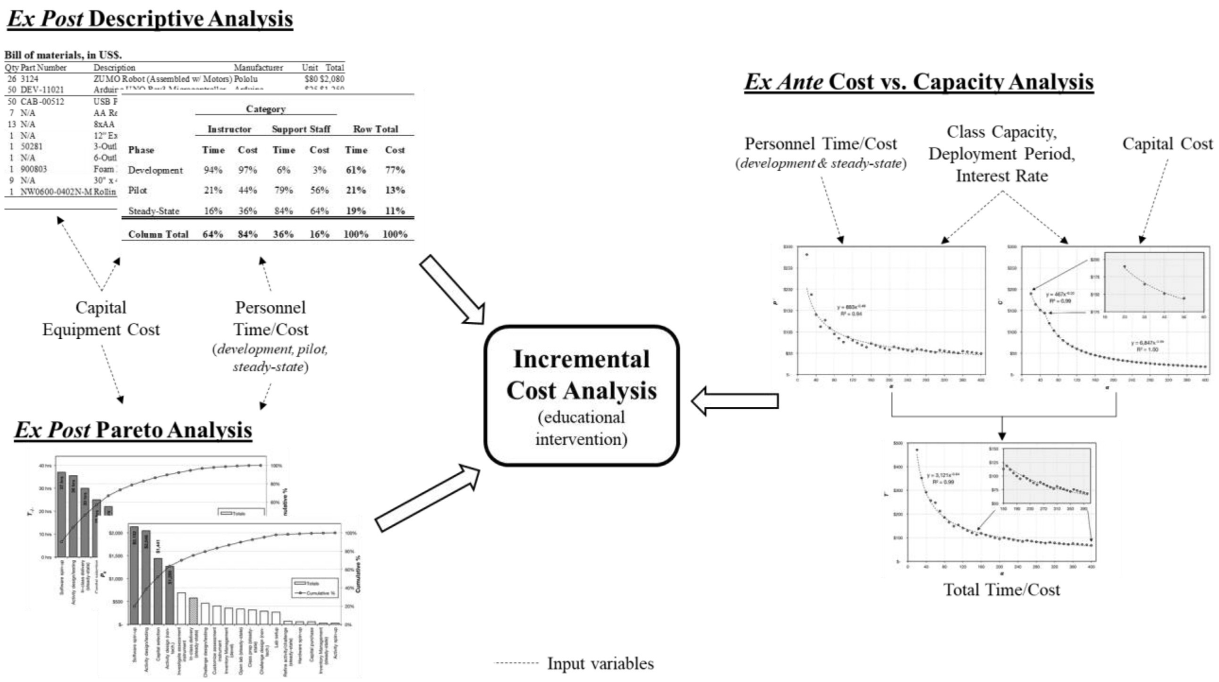

Fig. 1. Ex post and ex ante elements used in the author's incremental cost analysis.

phases of the intervention, as well as *ex ante* scalability of costs per capacity forecasted four years into the future. The Results and Discussion section presents a proto-typical educational experiences in mechatronics to illustrate the practical application of our method and associative limitations. Finally, the Conclusion section discusses recommendations regarding the *ex post* and *ex ante* analysis of our mechatronic experience, and a summary of our results.

3. Materials and methods

To help clarify the application of our method, we present both the illustration in Fig. 1 and example data from a study focusing on the costs and scalability of a mechatronic experience in a first-year undergraduate engineering technology course offered at a large Midwestern university in the United States of America [21]. Our data represent the incremental *personnel* and *equipment/material* (capital) costs incurred by the experience that were above and beyond the *status quo* educational costs, as defined by Levin and McEwan's [9] costs "ingredient" approach. These data were collected over a 13-month period during the *development* (March–October 2015), *pilot* (October 2015–January 2016), and *steady-state* (February–May 2016) phases of our experience, per the Institute of Education Science's *Common Guidelines for Educational Research and Development* [22] protocol. Furthermore, all costs were discounted to 2015 US$ nominal values.

3.1 Personnel

Personnel expenditures were comprised of instructor and support staff—teaching assistants (TAs), lab technical staff, and administrative support staff—time and costs. One instructor developed the mechatronic experience. During the *pilot* and *steady-state* phases, data were collected from this single instructor, who also was teaching four course sections (35–48 seats per section) over a two-semester period with one additional TA per section. Personnel cost (P_k) in 2015 US$ accrued during the *development*, *pilot*, and *steady-state* phases of the study were calculated to the nearest dollar using Equation 1,

$$P_k = \sum_{k=1}^{3}\left[T_{ijk}\left(\frac{S_i}{Y_i}\right)1.51\right] \qquad (1)$$

where T_{ijk} is the time (hours) expended by i^{th} personnel category, on j^{th} task, during k^{th} phase, with k taking on the values of 1 = *development*, 2 = *pilot*, and 3 = *steady-state*; S_i is the median base salary (2015 US$) of engineering and engineering technology faculty members [23] per i^{th} personnel category, and Y_i is the time (hours) worked per year per i^{th} personnel category. The 1.51 is an indirect cost multiplier [24]. Support staff yearly times were estimated at 2,080 hours (i.e., 52 weeks per year at 40 hours per week) and instructor yearly time was estimated at 2,196 hours (i.e., 9 months per year at 4 weeks per month at 61 hours per week). The 61 hours per week for instructor time was based on the lone study by Ziker et al. [25] that has characterized time allocations of nine month tenure-track faculty. For example, using Equation 1, with values of T_{ijk} = 4 hours, S_i = \$83,808, Y_i = 2,169 hours, we calculated personnel costs (P_k), for the instructor (i = instructor), during the *pilot* phase (k = 2), while completing class preparation tasks (j = Class prep (pilot)), to be equal to \$202 (Table 3).

3.2 Capital

The capital equipment used in our experience is illustrated in Table 1. These items were selected based on a review of relevant literature [1], instructor input, and professional experience. As with personnel time, the bill of material (BOM) only included items beyond the course's baseline capital equipment requirements and was divided into the subcategories of *robot platform* (RP) and *support equipment* (SE). The equipment list was developed for a maximum course section capacity of 50 seats, with one Arduino (Arduino, USA) microcontroller per seat, one ZUMO (Pololu, Las Vegas, NV) robot chassis per two seats, and the remaining ZUMO for instructor demonstration. This equipment was shared across four course sections (121 total seats) during the *pilot* and *steady-state* phases of the study. The capital cost (C) in 2015 US\$ of this equipment was calculated to the nearest dollar using Equation 2,

$$C = \sum_{i=1}^{n} (A_i) k_i \tag{2}$$

where A_i is the acquisition cost, including tax, per i^{th} equipment item, k_i is the unit quantity per i^{th} equipment item, and n is the total number of items.

3.3 Data analysis

To facilitate preliminary *ex post* incremental costing, we conducted a descriptive analysis of the per phase, position, and category times and costs (Table 2 and Table 3) of our mechatronic experience. From this we move to Pareto analysis [26] to identify the vital few (~20%) personnel tasks and capital items that contributed to a majority (~80%) of the overall time and cost of the mechatronic experience. Defining these cut points was accomplished by identifying the first drastic step-down between adjacent bars of the Pareto chart [27]; in instances lacking a drastic step-down, a threshold at the 60% cumulative mark can denote items comprising the vital few [27]. This analysis isolates the vital few tasks and items that should be tracked on even the most rudimentary cost analysis. A discussion of these key tasks and items given in the Results & Discussion section below.

To conduct *ex ante* analysis, we estimated incremental per seat costs in 2015 US\$ for personnel (P'),

Table 1. Mechatronic equipment bill of materials, in 2015 US\$

Qty	Part Number	Description	Manufacturer	Reference Link	Unit	Total	Sub*
26	3124	ZUMO Robot (Assembled w/ Motors)	Pololu	http://goo.gl/Yuqdwm	\$80	\$2,080	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	SE
7	N/A	AA Recharge Batt., 2100mAh, 16 pc	Rayovac	http://goo.gl/57EmB5	\$30	\$210	SE
13	N/A	8 × AA Battery Charger, NiMH	Rayovac	http://goo.gl/j9o2RD	\$10	\$130	SE
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-Outlest Surge Protector, 2 pk	AmazonBasics	http://goo.gl/DumuKJ	\$12	\$12	SE
1	900803	Foam Board, 10pk	Elmer's	http://goo.gl/gmIBvV	\$55	\$55	SE
9	N/A	30″ × 40″ Project Course, B/W	Campus Printing	N/A	\$5	\$47	SE
1	NW0600-0402N-M	Rolling Storage Case	Lista	N/A	\$787	\$787	SE
					Total:	\$4,736	

* RP = Robot Platform, SE = Support Equipment.

Table 2. Summary of percentages of time (T_{ijk}) and cost (P_k) per phase, position, and task by category

	Category					
	Instructor		Support Staff		Row Total	
Phase	Time	Cost	Time	Cost	Time	Cost
Development	94%	97%	6%	3%	**61%**	**77%**
Pilot	21%	44%	79%	56%	**21%**	**13%**
Steady-State	16%	36%	84%	64%	**19%**	**11%**
Column Total	**64%**	**84%**	**36%**	**16%**	**100%**	**100%**

Table 3. Summary of time (T_{ijk}) and cost (P_k) per phase, position, and task by category, in 2015 US$

			Category						
Phase	**Position**	**Task**	**Instructor**		**Support Staff**		**Row Totals**		
Development			**161 hrs**	**$9,249**	**11 hrs**	**$248**	**171 hrs**	**$9,497**	*77%*
	Admin Support Staff				**2 hrs**	**$57**	**2 hrs**	**$57**	
		Capital purchase			2 hrs	$57	2 hrs	$57	
	Instructor		**161 hrs**	**$9,249**			**161 hrs**	**$9,249**	
		Activity design (non-tech.)	22 hrs	$1,268			22 hrs	$1,268	
		Activity design/testing	36 hrs	$2,046			36 hrs	$2,046	
		Capital selection	25 hrs	$1,441			25 hrs	$1,441	
		Challenge design (non-tech.)	5 hrs	$288			5 hrs	$288	
		Challenge design/testing	8 hrs	$461			8 hrs	$461	
		Customize assessment instrument	7 hrs	$403			7 hrs	$403	
		Hardware spin-up	1 hrs	$58			1 hrs	$58	
		Inventory Management (devel)	5 hrs	$259			5 hrs	$259	
		Investigate assessment instrument	12 hrs	$692			12 hrs	$692	
		Lab setup	4 hrs	$202			4 hrs	$202	
		Software spin-up	37 hrs	$2,132			37 hrs	$2,132	
	Lab Tech Staff				**2 hrs**	**$66**	**2 hrs**	**$66**	
		Lab setup			2 hrs	$66	2 hrs	$66	
	Teaching Assistant (TA)				**7 hrs**	**$125**	**7 hrs**	**$125**	
		Activity spin-up			2 hrs	$29	2 hrs	$29	
		Inventory Management (devel)			5 hrs	$96	5 hrs	$96	
Pilot			**12 hrs**	**$692**	**46 hrs**	**$883**	**58 hrs**	**$1,574**	*13%*
	Instructor		**12 hrs**	**$692**			**12 hrs**	**$692**	
		Class prep (pilot)	4 hrs	$202			4 hrs	$202	
		Evaluate assessment data (pilot)	5 hrs	$259			5 hrs	$259	
		Refine activity/challenge (pilot)	4 hrs	$231			4 hrs	$231	
	Teaching Assistant (TA)				**46 hrs**	**$883**	**46 hrs**	**$883**	
		Class prep (pilot)			4 hrs	$77	4 hrs	$77	
		In-class delivery (pilot)			28 hrs	$537	28 hrs	$537	
		Inventory Management (pilot)			4 hrs	$77	4 hrs	$77	
		Open lab (pilot)			10 hrs	$192	10 hrs	$192	
Steady-State			**8 hrs**	**$475**	**45 hrs**	**$854**	**53 hrs**	**$1,329**	*11%*
	Instructor		**8 hrs**	**$475**			**8 hrs**	**$475**	
		Class prep (steady-state)	6 hrs	$317			6 hrs	$317	
		Inventory Management (steady-state)	1 hrs	$29			1 hrs	$29	
		Open lab (steady-state)	2 hrs	$86			2 hrs	$86	
		Refine activity/challenge (steady-state)	1 hrs	$43			1 hrs	$43	
	Teaching Assistant (TA)				**45 hrs**	**$854**	**45 hrs**	**$854**	
		In-class delivery (steady-state)			30 hrs	$576	30 hrs	$576	
		Open lab (steady-state)			13 hrs	$249	13 hrs	$249	
		Refine activity/challenge (steady-state)			2 hrs	$29	2 hrs	$29	
Column Totals			**181 hrs**	**$10,416**	**101 hrs**	**$1,985**	**282 hrs**	**$12,401**	

capital (C'), and total personnel and capital (T'). These estimates were performed using a four-year deployment period, and are illustrated in Equation 3a, 3b, and 3c,

$$P' = \frac{\frac{P_1(1+r)^n}{n} + \frac{mP_3}{1}}{\alpha} \tag{3a}$$

$$C' = \frac{[C + (\alpha)R](1+r)^n}{\alpha} \tag{3b}$$

$$T' = P' + C' \tag{3c}$$

where P_1 and P_3 are *development* and *steady-state* phase personnel costs, respectively; α is the yearly seat capacity and takes values from 20 to 400, in increments of 10; *development* cost is amortized based on a simple future value using an August 2015 interest rate (r) of 0.11 [28] with a deployment period (n) equal to four years; *steady-state* instructor and TA costs repeat every *mth* course sections in discrete increments of 50 seats; capital and repair costs are amortized using a simple future value; and R is the repair cost multiplier per seat, calculated using Equation 4,

$$R = \frac{2(r_A)}{121} \tag{4}$$

where r_A is the repair cost of $19.95 that was accrued (2015 US$) during the first year of deployment (*pilot* and *steady-state*) to 121 seats with a safety factor of two. This method of calculating a repair cost multiplier based on historical repair costs was assumed to be the best estimate of future repair costs [29]. No salvage value adjustments were made to the total cost at the end of the deployment period. Equations 3a–3c then allowed us to quantify how costs scaled with per year seat capacities (i.e., per year class size). To do this, we used a power function model, as illustrated by Equation 5,

$$y = k(x)^a \tag{5}$$

where y is the cost (2015 US$) calculated using Equation 3a, 3b, and 3c, k is the constant of proportion of cost (2015 US$), x is the capacity (i.e., per year number of seats), and a is the power factor describing the incremental scaling relationship between cost and capacity. This analysis was borrowed from the chemical processing industry, where power factor modeling has been used for well over a half century. We feel it is well suited to the field of engineering education, as it allows for straight forward per seat (or per course section) incremental cost analysis for an experience. When looking at historical data from the chemical process industry, personnel costs divided by capacity have been found to commonly scale at a factor of $a = -0.60$ with 95% of observations ranging from $-1.00 \leq a < -0.40$, while equipment capital costs divided by capacity typically scale at a factor of $a = -0.40$ with 95% of observations ranging from $-0.70 \leq a < 0.10$ [30]. We compared our results with these scaling factors and intervals, due to the lack of evidence available in the literature related to educational intervention costing.

4. Results and discussion

4.1 Ex post descriptive: phase, position, and category

Over the 13-month study period, the overall time and cost for *development*, *pilot*, and *steady-state* phases of the mechatronic experience were close to 280 hours and slightly over $12.4k, respectively (Table 3). Separating these totals by phase, *development* totaled 171 hours (61% of total time, Table 2) and $9,497 (77% of total cost), *pilot* phase totaled 58 hours (21% of total time) and $1,574 (13% of total cost), and *steady-state* totaled 53 hours (19% of total time) and $1,329 (11% of total cost). As expected, *development* time and cost were both greater than *pilot* or *steady-state* time and cost, with *development* times averaging nearly 3.0 and 6.5 times greater than either *pilot* or *steady-state* time or cost, respectively (Row Total, Table 2). *Pilot* and *steady-state* time and cost were nearly equal, with *steady-state* being slightly lower, reflecting slight returns on training investments made during the *pilot* phase. Total instructor time and cost were 1.8 and 5.2 times greater than support staff time and cost, respectively (Column Total, Table 3). These ratios shifted across phases, with *development* phase instructor time and cost being 15 and 37 times greater than *development* phase support staff time and cost, respectively (Column Total, Table 3). During the latter two phases, total support staff time and costs averaged 4.7 and 1.5 times greater than instructor time and costs, respectively (Column Total, Table 3). This analysis reveals that 1) most of the personnel expenditures in this study were attributed to instructor time and cost during the *development* phase, and 2) most of the *pilot* and *steady-state* phase time and cost were attributed to support staff (specifically TA time and cost). These results are expected, as the largest amount of personnel expenditures are commonly spent during the *development* phase of an experience (i.e., design planning and design execution) [31].

4.2 Ex post pareto: personnel and capital

The Pareto charts in Fig. 2 and Fig. 3 illustrate the tasks that were performed across the *development* and *steady-state* phases of the mechatronic experience's deployment. Examining the times per task in Fig. 2, five (28%) were identified as vital (gray bars). These items accounted for the majority (67%) of the aggregate personnel time. Analyzing costs per task in Fig. 3, four (22%) were identified as vital (gray bars). The first major difference evidenced by these results is the hatched bar task in this figure (i.e., *In-class delivery (steady-state)*). The time for this task was significant, however, its associated cost was not. (It was performed by the TA position, which had the lowest calculated hourly rate.) The TA's critical role in delivering the mechatronics content should not be overlooked. Students commented in their end of semester course evaluations that the TA's in-class support (e.g., answering questions or helping troubleshoot system functionality) was significantly beneficial to their learning. The instructor performed all the other vital tasks, which included *Software spin-up, Activity design/ testing, Capital selection*, and *Activity design (non-tech.)*. These results are unsurprising, due to the complexity of mechatronics systems, which require the integration of multiple technical domains [2]. From this Pareto analysis, we identified the primary personnel tasks to be tracked are the *instructor's* time and cost during the *development* and *steady-state* phases, as well as the TA's time and cost during the *steady-state* phase of an engineering education experience.

Examining capital costs (C) per BOM item, the

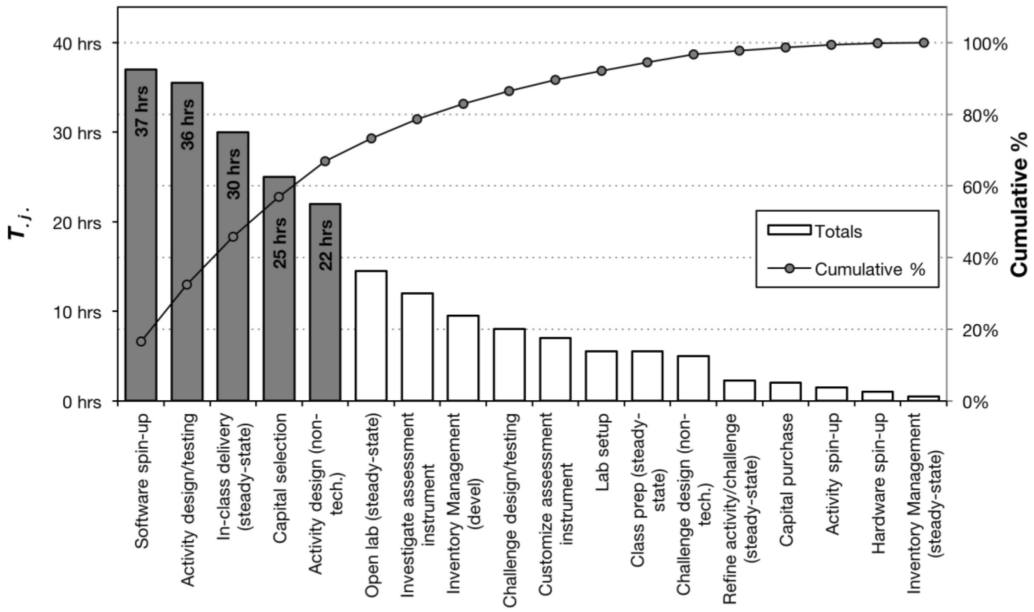

Fig. 2. Pareto chart of personnel task time ($T_{.j.}$).

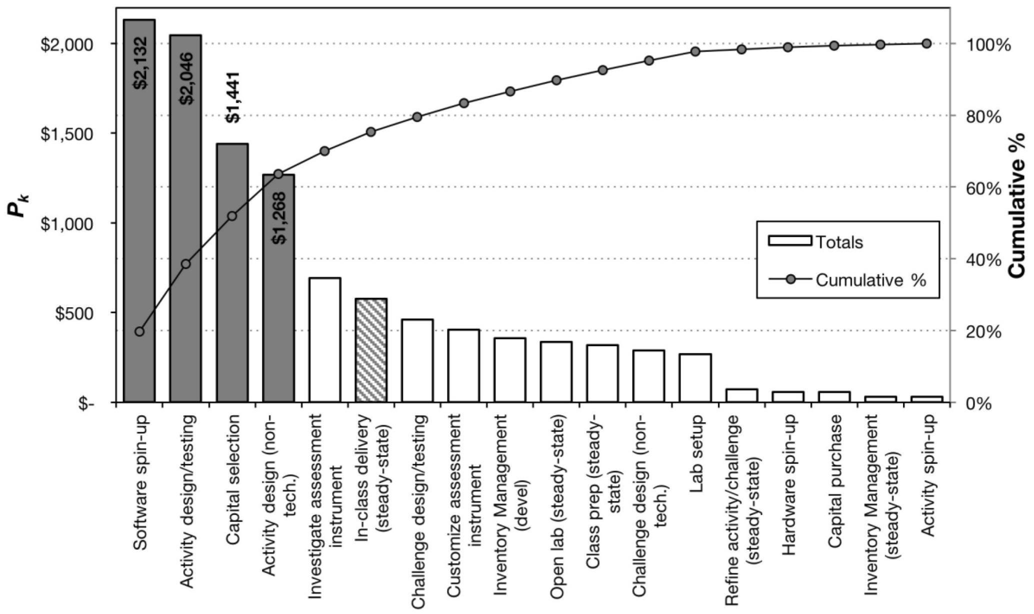

Fig. 3. Pareto chart of personnel task cost (P_k).

Pareto chart in Fig. 4 illustrates the ZUMO robot chassis, Arduino microcontroller, and rolling storage case were the vital few (gray bars) that accounted for the significance of capital costs. These items (30%) comprised \$4,117 (87%) of capital costs (Table 1). Apart from the storage case, this was not surprising, as the chassis and microcontroller were the most technically advanced items. Moreover, while these RP items were of primary importance from a cost perspective, their selection also drove much of the remaining BOM design (e.g., SE requirements) and affected spin-up time (e.g., software spin-up requirements) during the *development* phase. Consequently, these items were considered the primary time and cost drivers. Considering the significance of the rolling case, this item was logistically instrumental in the organization and delivery of the mechatronic experience. Speaking to more generic incremental cost analyses, we suggest (at a minimum) tracking the costs for the most "intricate", "complex", "advanced" pieces of equipment that are used in an experience.

4.3 Ex ante cost vs. capacity

All of our *ex ante* power function models for personnel costs (P'), capital costs (C'), and com-

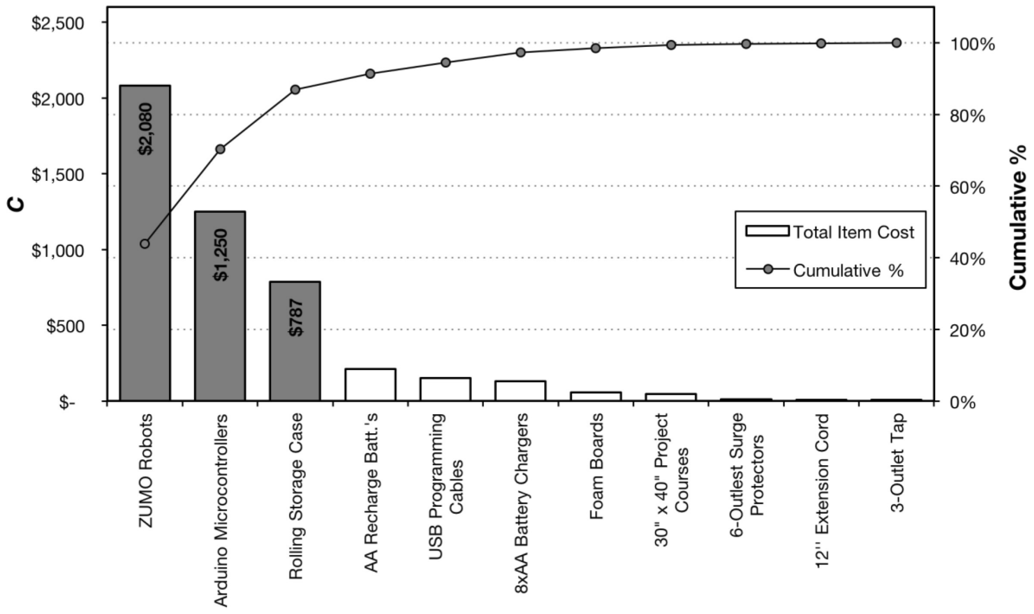

Fig. 4. Pareto chart of capital cost (C) per BOM item.

bined total costs (T') were based on data attained from results of Equations 3a, 3b, and 3c, respectively. The reader will recall these equations account for *development* (P_1) and *steady-state* (P_3) phase personnel costs, a simple future value of money for capital costs (using an interest rate of 0.11 (r)), deployment period of four years (n), repair costs (R), and TA cost increments (m) added at discrete student capacities (α) of 50. Student capacities ranged from 20 to 400, in increments of 10. For example, using Equation 3a, P' = \$88 at $\alpha = 80$ students (Fig. 5), while C' = \$151 at $\alpha = 40$ students (Fig. 6).

4.3.1 Personnel cost vs. seat capacity

Fig. 5 illustrates the cost structures of per seat personnel costs (P') per yearly seat capacity (α). Looking at the scaling factor of the P' vs. α curve ($y = 883x^{-0.49}$), it was within the chemical industry's 95% interval for observations of personnel costs vs. capacity ($-1.00 \le a < -0.40$), as reported above in section 3.3 Data analysis [30]. This resulted in a

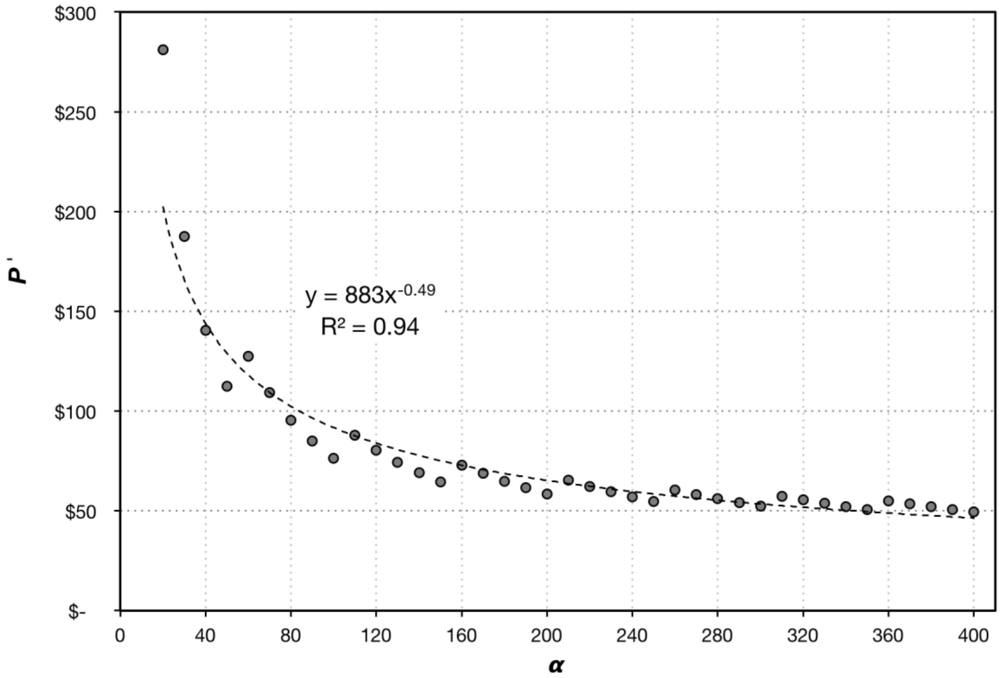

Fig. 5. Per seat personnel costs (P') per seat capacity (α).

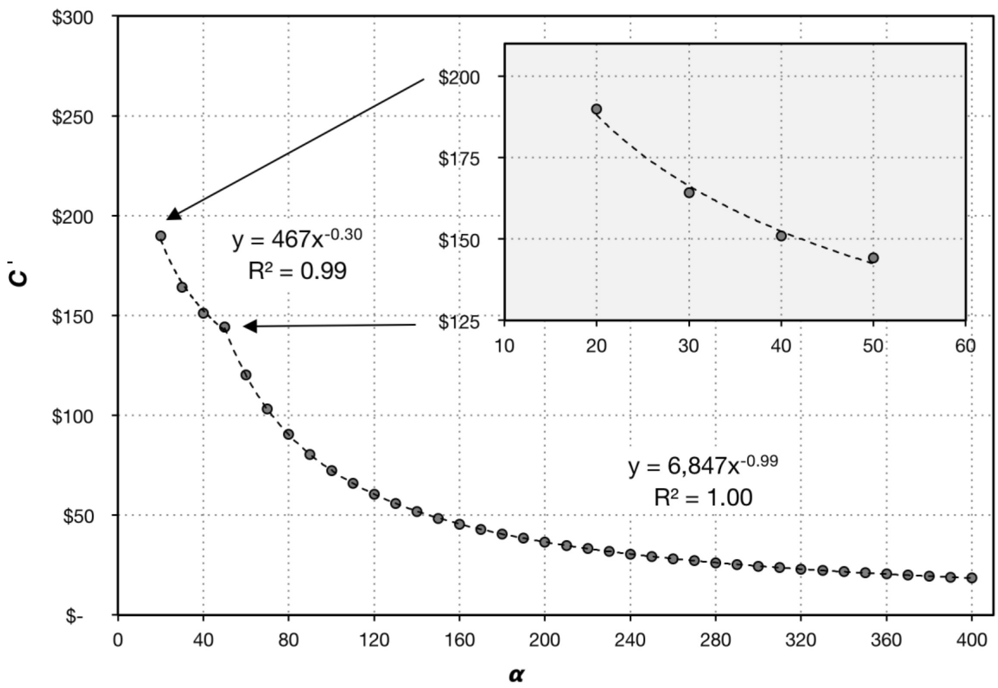

Fig. 6. Per seat capital costs (C') per seat capacity (α); inset chart illustrates a close-up of the cost curve of per seat capital between the capacities of 20–50 seats.

range of per seat personnel costs of roughly $280–$50, with our mechatronic experience coming in at just over $85 per seat (based on a capacity of 117 students). Specifically, personnel costs were estimated to decrease by a power of 0.49 for every additional seat, except when the capacity crosses 50 seat intervals. At these points, the P' vs. α curve has a saw-toothed profile, reflecting the discontinuous personnel costs during the *steady-state* phase of the mechatronic experience. These discontinuities occur because we added an additional instructor and TA per increment of 50 seats to the *steady-state* time. This was done to support student learning, which has been shown to be negatively correlated with section size [32]. At these break points, the variable personnel costs increased by roughly $5–

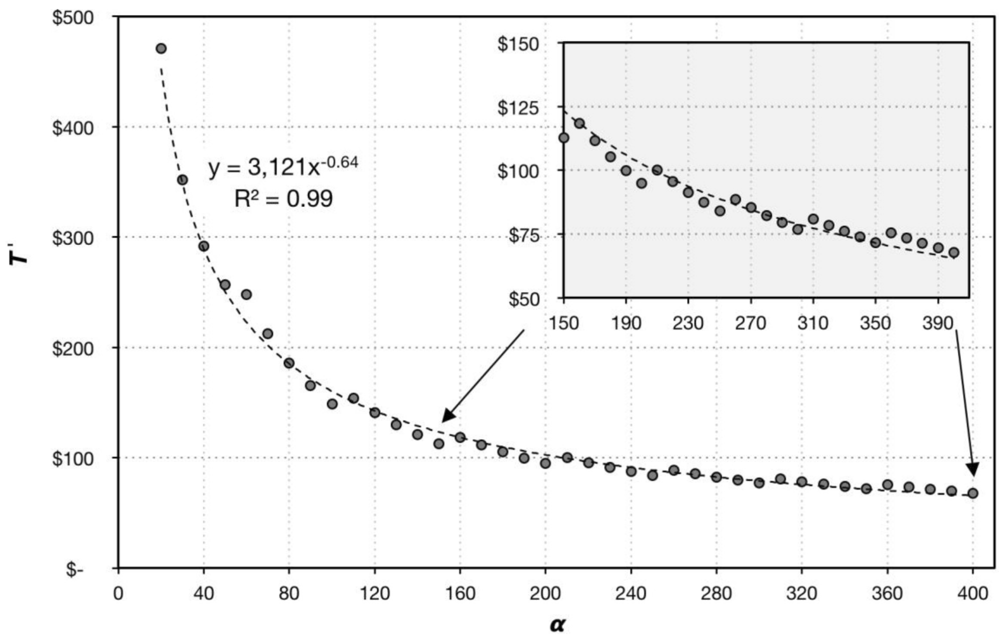

Fig. 7. Total per seat total cost (T') per seat capacity (α); inset chart illustrates a close-up of the cost curve of per seat total cost between the capacities of 150–400 seats.

\$10 per seat, indicating possible inherent upper limits for α, similar to inherent upper physical limits of chemical process equipment (i.e., maximum allowable size) [33]. The gradual downward slope of the P' per α curve was attributed to the fixed personnel costs during the *development* phase that were amortized across the four-year estimation period. These findings support an economic rationale for increased section quantities, not section capacities. Based on this, we recommend adding class sections if seat numbers increase beyond a set class size of 50 seats for a mechatronic experience.

4.3.2 Capital cost vs. seat capacity

Estimating per seat capital costs (C') across a range of per year seat capacities (α) resulted in the cost curve in Fig. 6. For capacities at or below the maximum section size of 50, C' per α scaled at a factor of –0.30 ($y = 467x^{-0.30}$, $R^2 = 0.99$). This means that for every additional seat (up to 50) the cost decreased by a power of 0.30. This was also within the 95% interval for observations of capital costs vs. capacity seen in the chemical processing industry [30]. However, as the capacity increased above 50 seats, the capital costs decrease by a power of –0.99 (outside the 95% interval [30]) for every additional seat ($y = 6{,}847x^{-0.99}$, $R^2 = 1.00$). This resulted in a range of per seat capital costs of roughly \$200–\$20, with our mechatronic experience coming in at just over \$60 per seat. Similar to the curve for personnel costs, the curve for capital costs indicated an inherent upper limit of seat capacity, which altered the economies of scale. This was not surprising, and was due to the sharing of equipment across multiple class sections, that effectively converted these to fixed costs. Therefore, to reflect this break point in α, the C' per α curve in Fig. 6 was segmented at $\alpha = 50$ to enable a more appropriate fit of the data. These results supported both the sharing of equipment across multiple course sections, which reduced the per seat cost of the mechatronic experience, and the use of multiple course sections as seat capacities are increased.

4.3.3 Total cost per seat capacity

Per seat total cost (T') per yearly seat capacity (α) is illustrated in Fig. 7. Analysis of this figure reveals much of the same structures for fixed and variable costs as discussed for Fig. 5 and Fig. 6. However, unique to Fig. 7, T' increased at a scale factor based on the combination of P' ($x^{-0.49}$) and C' ($x^{-0.89}$, based on an unsegmented curve) data sets. Interestingly, T' per α scaled at a factor of –0.64 ($y = 3{,}121x^{-0.64}$, $R^2 = 0.99$), which was within the expected scaling intervals for both personnel and equipment costs per capacity [30], and resulted in a range of per seat costs of roughly \$470–\$70. The per seat total cost for our mechatronic experience averaging at just under \$150. The profile of this curve can be attributed to the same underlying causes as discussed above (i.e., *development* phase personnel costs being fixed and amortized across all α while *steady-state* personnel costs varied in discrete steps of roughly \$5 per seat as α increased). So, whether our data is analyzed in part or in total, there appeared to exist key break points in class size that have the potential to influence the economic (i.e., cost per seat) and logistic (i.e., personnel time per seat capacity) feasibility of implementing a mechatronic experience.

5. Limitations and future research

The methods for incremental cost analysis that we used were conducted with an effort towards equity and objectivity. However, inherent limitations still exist in our methods that have the potential to impact the results. For example, our study did not consider intangible costs or benefits related to instructional quality or student learning outcomes, even though these factors represent authentic variables in a full CBA or CEA analysis. Therefore, we recommend further research to specifically delineate and quantify the outcome of academic success per costs incurred to develop, pilot, and deploy educational experiences. In so doing, a full CEA could be conducted to include CERs of *ex post* costs one— and multi-year deployments per effect, as well as *ex ante* costs of per seat capacities per effect. This would give educational decision makers a fuller understanding of the costs, scalability, and impacts of educational experiences.

The experience level of the instructor tasked with the *development* phase design and spin-up was not included as a variable in the analysis. The instructor in this study had roughly ten years of experience in mechatronic systems integration in a variety of manufacturing and process industries, as well as three years of experience teaching fundamental engineering technology courses. However, the instructor did not have any previous experience with the equipment items and related software tools used in this study. While this variable is expected to affect personnel time and cost (i.e., experience inversely proportional to time and directly proportional to cost), more research is needed to quantify its effects before it is included in an incremental cost analyses.

Furthermore, the factors of interest rate (r), instructor salary (S), and intervention deployment period (n), used in our *ex ante* estimates of per seat total costs (T') exhibited variability. Even though the purpose of this *ex ante* analysis was not to develop a generalizable scaling model for all educational interventions, we did want to assess the impact of the variability of these inputs on the validity of our model. Therefore, we performed simple range sensitivity analysis on these factors to test whether there were significant differences ($\alpha = 0.05$) in our model results (T'). Applying a $\pm 10\%$ adjustment to the interest rate (r) obtained from [28] (i.e., $r = 0.10$ vs. $r = 0.11$ vs. $r = 0.12$) had no statistical impact on our model's per seat total cost results [F(2,114) = 0.14, p-value = 0.8698]. Adjusting the instructor salary (S) (i.e., $S_{minimum}$ = \$69,665 vs. S_{median} = \$83,808 vs. $S_{maximum}$ = \$129,012, based on [23]) did not produce statistically different results in our model's per seat total costs [$F(2,114)=1.35$, *p-value* = 0.2625]. Changing the intervention deployment period (n) (i.e., n = 1 vs. n = 2 vs. n = 4 vs. n = 8 vs. n = 16) did not statistically alter the results to per seat total costs [$F(4,190)=1.74$, *p-value*=0.1437]. We inferred from these results that the variability in interest rate, instructor salary, and intervention deployment period did not present a significant risk to the results of our per seat total cost model (Fig. 7). While these variables are expected to differ per institution and personnel, they did not appear to not have a detrimental impact on the viability of our per seat total cost power function model.

6. Recommendations

The methods presented in this paper quantified the costs and scalability of an example experience in an undergraduate course. These form the building blocks of a full CEA, which allow educators to answer real questions of cost verse effect, such as: "Is an education experience worth it?", "Does the effects or benefits of an educational experience outweigh its costs?", or "What is the expected cost per unit effect or cost per unit benefit of an educational experience?" These questions are important and should be asked when evaluating engineering education initiatives, especially considering the continued decline of government funding for higher education. As educators are asked to accomplish more with less, understanding the costs associated with an initiative is vital. We argue that only when researchers adopt and practice the methods of incremental cost analysis of educational initiatives will they have the ability to make truly informed, sustainable, and effective decisions.

7. Conclusions

In this paper we presented a structured method of incremental cost analysis for an engineering education experience. Specifically, we proposed the collection of cost data for *personnel* and *equipment/materials*, and proposed a method for examining these costs, namely *ex post* and *ex ante* analyses. Using a representative mechatronic experience from a fundamental engineering technology course, we performed *ex post* descriptive and *ex post* Pareto analyses that identified the vital phases, personnel tasks, personnel categories, and capital equipment that contributed to the majority of the incremental costs of our experience. From this we found that the instructor's *development* phase time and cost, as well as the robot chassis and microcontroller capital cost were the primary economic drivers of the experience. Evaluating *ex ante* estimates of personnel and capital costs per yearly seat capacities using power function models, we found that cost vs. capacity (for both personnel and capital) scaled at a factor within the 95% intervals commonly observed in the chemical processing industry. Our *ex ante* analysis illustrated key break points in the economic structures of the experience (i.e., cost curve profiles of Fig. 5, Fig. 6, and Fig. 7). These break points were due to upper limits of seat capacity, that have the potential to positively impact the feasibility of implementing a mechatronic experience. Furthermore, we argued that by sharing equipment across class sections, the per seat cost can be reduced, while increased personnel time and cost is needed at key class capacity break points. We hope our research will provide a straightforward method for assessing intervention costs in engineering education.

Acknowledgements—We would like to thank the Department of Agricultural and Biosystems Engineering at Iowa State University for the generous financial support of this project, as well as the thoughtful and insightful comments of the *Journal's* reviewers.

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