Incorporating a Model-Based Approach in an Introductory Electronics Course Using Simscape

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***Abstract*— The teaching of circuits and electronics courses has historically been supplemented with circuit simulation software such as PSpice, Multisim, among others. In this Innovative Practice Full Paper we describe our experience in teaching an introductory electronics course with MATLAB Simscape, a software tool that allows for physical and multibody modeling of systems. We decided to try Simscape in our electronics course because of the system modeling capabilities of the tool and its seamless integration with MATLAB Simulink, another tool used by students in subsequent courses (e.g., control systems, communications, signal processing, and so on). We present the simulation experiments (half-wave rectifier, offset and gain amplifier, BJT/MOSFET inverter, and PWM DC motor speed control) that were created in order to acquaint the students with Simscape. In addition, we collected data from past offerings of the course to compare with the Simscape-supplemented course; results reveal slight improvement in students' performance. We also surveyed the students to obtain their impressions about the effectiveness of the model-based approach at reinforcing conceptual understanding of the topics covered in the course.**

Keywords*— *MATLAB Simscape, electronics, model-based approach

I. Introduction

Model-based learning or teaching has proven to be very beneficial to learners. With solid foundations supported by the cognitive sciences, the use of system models and simulations helps individuals to improve understanding and problem solving in complex domains [1]. The strength of the model-based approach lies in the support of the development and evolution of the individual's internal representations of integrated knowledge known as mental models; this integrated knowledge allows learners to understand the interactions between components of dynamical systems and overall system behavior [2]. Model-based learning —whether it be in the form of mathematical models, computer simulations, manipulatives, prototypes, and so on— has been successfully utilized in the teaching of science [3] and engineering courses [4].

The model-based approach in engineering has typically relied on mathematical models of physical systems and computer simulations. Simulation or computer experimentation is an effective investigative tool for understanding the interactions between the subsystems or components that comprise complex systems, thereby leading to the emergence of models that explain the behavior of such systems. In the context of the teaching of electrical engineering courses, the computer simulation of electric and electronic circuits has been largely dominated by the use of PSpice and Multisim [5]–[7]. These tools provide the user with the building blocks for constructing and simulating circuit models on a computer. The wide adoption of these circuit simulators has enhanced the learning experience of myriads of students. In spite of the tangible benefits of PSpice or Multisim in instruction delivery, educators have been exploring other alternatives. In recent years, MATLAB Simscape has been incorporated in the classroom; for instance, [8] reports on the use of Simscape in power electronics and electrical machines courses. This is perhaps not entirely unexpected as Simscape has been used in research settings as a model-based system design and simulation tool [9]–[14].

In following these recent developments in electrical engineering education, we decided to explore the possibility of using a model-based approach in some of the circuits courses at our institution. Thus, in the spring 2017 semester we incorporated Simscape to our introductory undergraduate electronics course (namely, ELEN 330 – Electronics I). While we interspersed our lectures with Multisim in past offerings of the course, we felt that exposing students to delve deeper into the mathematical models (i.e., governing equations) of the functional blocks provided by circuit simulators would add another dimension to the students' experience. In Simscape we found an ideal tool for our model-based approach to teaching basic electronics. It was our experience that having used Simscape by no means detracted from the successful experiences observed in the past with Multisim. Another advantage of Simscape is that it can seamlessly integrate to MATLAB and Simulink. Indeed, having our students learn Simscape will help them in subsequent courses such as controls, power electronics, signal processing, and communications in which MATLAB and Simulink are extensively used.

In this paper we describe how we implemented the model-based approach in our electronics course. We also conducted a comparative analysis of students' performance and a student survey to obtain their impressions about the effectiveness of the model-based approach. The paper is organized as follows. In Section 2 we briefly describe the modules that were developed (half-wave rectifier, offset and gain amplifier, BJT/MOSFET inverter, and PWM DC motor speed control) to implement our model-based instructional method. In Section 3 we report the results of our comparative analysis of students' performance; also included here are the results of the student survey. Finally, in Section 4 we give some concluding remarks.

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II. IMPLEMENTATION OF THE MODEL-BASED APPROACH

Our introductory course in electronics and microelectronics (ELEN 330) aims to build a solid understanding of basic electronic devices. The course covers topics in fundamentals of semiconductors, operational amplifiers, diodes, BJTs, MOSFETs, and basic digital switching, with the main purpose of providing a clear understanding of device operation on a physical level, and then complementing this knowledge with applications, analysis, and design of electronic circuits. The course requires the use of modern engineering tools to model and design practical electronic circuits, with Multisim being the widely preferred tool by instructors at our university.

As stated earlier, we decided to use Simscape Electronics —a Matlab/Simulink modeling environment— in our course. We created four models using basic blocks integrated with the Simscape toolbox, and prepared written material containing guidelines for constructing the models, screen captures of block diagrams, circuit schematics, and exploratory questions. Students had to build these models and perform simulations to complete the required tasks. We took this approach in order to make students aware of the importance of block interconnections, signal flows, numerical solver configuration, and so on. These models were carefully selected to reinforce the main topics covered in our introductory electronics course, namely diodes, operational amplifiers, and transistors. To acquaint students with the computer modeling of electronic circuits, the course instructor offeres a Matlab/Simulink seminar each academic term where the Simscape toolbox is explained in detail so as to expose our students to an alternative tool, since some of them have no prior experience with the software. The four models that we developed are included in the course as homework assignments, with a deadline of one week prior to the partial exam where the topic concerning the experience with the software is evaluated.

Each homework requires students to answer questions comprising both basic concepts (handworked problems) and the simulation component to validate manual calculations. All models are variants of examples previously presented in class to allow students to focus on the conceptual ideas and then reinforce their understanding using the simulation environment through homework assigments.

It is pointed out that the building blocks that constitute the circuits examined in the homework assignments are highly customizable and its capabilities extensible to the point that governing equations may be modified by students to suit different types of analysis. Although modification of governing equations is not an explicit course objective, students do realize the usefulness of the model-based approach in solving complex engineering problems by altering the parameters that characterize the blocks while completing their assignments.

The four Simscape models are described below.

A. *Half-wave rectifier*

Figure 1 shows the model of a half-wave rectifier. An AC voltage source was used to generate a sinusoidal signal at 500 Hz with a peak amplitude of 25 V. The circuit was required to be simulated first with a purely resistive load of 10 Ω, and then with a 500 μF capacitor in parallel with the load resistor to evaluate the effect of the capacitor on the shape of the rectified signal. The "Goto" and "From" blocks (orange blocks) can be used for signal routing. A solver configuration block (yellow block) must be included in the model to perform the simulation. Each topologically distinct Simscape block diagram requires exactly one Solver Configuration block to be connected to it.

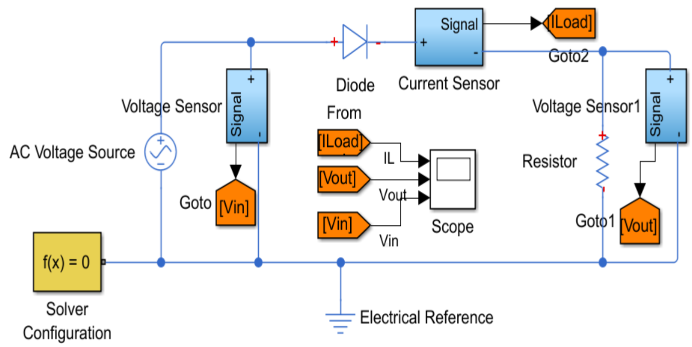

Fig. 1. Half-wave rectifier

Individual PS-Simulink Converter must be used to communicate both the voltage sensor and the current sensor with commonly used Simulink blocks. To facilitate the visualization, two subsystems were created (presented in Figure 1 as the blue blocks). The subsystems are shown in Figure 2.

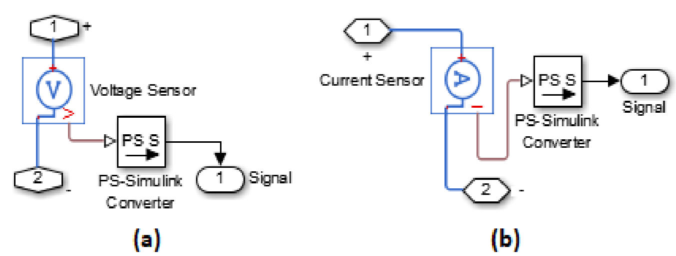

Fig. 2. Sensor subsystems: (a) voltage sensor, (b) current sensor

Figure 3 presents the different signals generated by the model, namely the input voltage, output voltage, and the output current— with and without the parallel capacitor. With these plots, students reinforce the topic covered in class by making observations and predictions about changing circuit parameters and how the changes may affect circuit behavior.

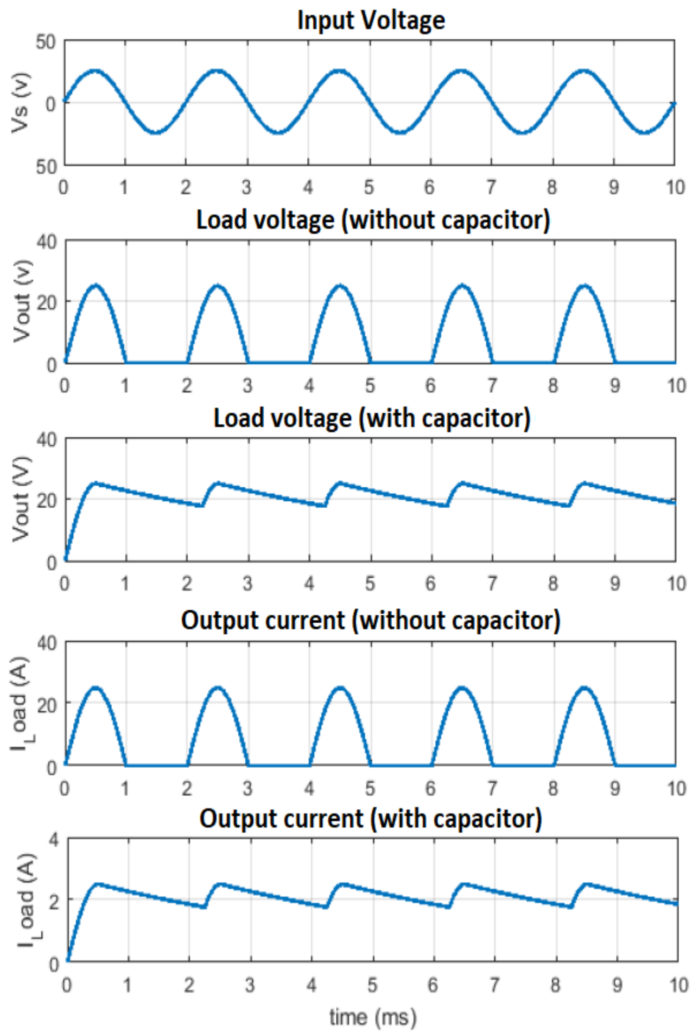

Fig. 3. Half-wave rectifier response without and with capacitor

B. *Offset and gain amplifier*

The goal of the second Matlab/Simscape module is to have students gain experience working with operational amplifiers (OPAMPs) through the construction of a circuit model commonly used for the hardware implementation of a general linear equation of the form $y = mx + b$, where the parameters m and b, respectively, play the role of the gain and offset in the opamp circuit. The actual formulation of the engineering problem that students are asked to tackle reads:

"A temperature sensor produces an output range of 2.48 V to 3.90 V for the complete desired response. Design a signal conditioning circuit to change the sensor output to a range of 0 V to 5 V to be processed by a microcontroller. The sensor has linear response."

The circuit implemented is shown in Figure 4. In this assignment, students have to simulate this circuit for both input boundary situations (2.48 V and 3.90 V) in order to verify that the circuit works properly and meets the design specifications.

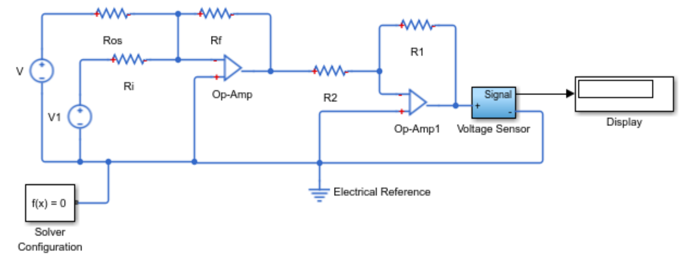

Fig. 4. Offset and gain amplifier

C. *BJT/MOSFET inverter*

Figure 5 demonstrates the use of a BJT and MOSFET as an inverter. A sinusoidal waveform input of 5 V peak at 1 Hz with the following parameter values were used in the implementation: $V_{CC} = V_{DD} = 10$ V, $R_B = 10$ kΩ, and $R_C = R_D = 470$ Ω. Students are asked to run simulations and comment about the output voltage for 3 cycles of the input signal for both circuits. The corresponding output waveforms are presented in Figure 6.

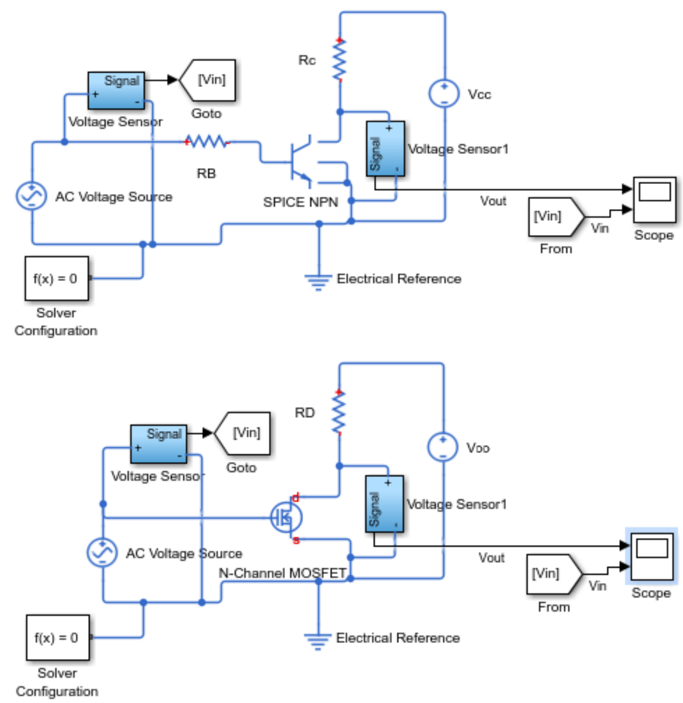

Fig. 5. BJT/MOSFET inverter

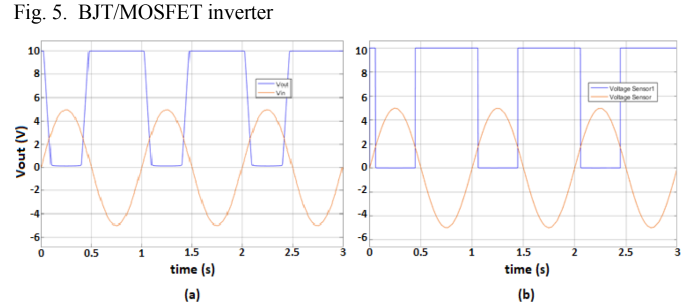

Fig. 6. Inverter response for: (a) BJT, (b) MOSFET

D. PWM DC motor speed control

Figure 7 illustrates the multi-domain capability of Simulink and Simscape by using basic blocks available in the Simscape environment. The components shown in blue and green, respectively, denote the defined electrical and mechanical domains which allow the students to perform a multi-domain simulation and obtain the system response in one single environment.

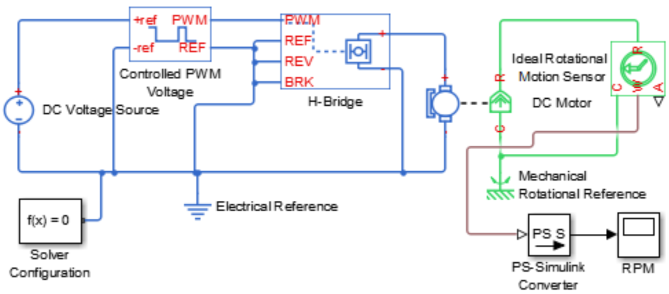

Fig. 7. PWM DC motor speed control

A separate reference block is required for each domain (electrical and mechanical). The electrical and mechanical parameters used in the DC motor are presented in Table I. A DC source of 2.5 V and a controlled PWM voltage block configured in the averaged simulation mode with a frequency of 4 kHz and an amplitude of 5 V were required. The H-Bridge block must be set to work on averaged simulation mode to generate an output signal whose value is the average value of the PWM signal. To obtain the desired output, an Ideal Rotational Motion Sensor must be included.

TABLE I. MOTOR BLOCK PARAMETERS

Electrical	Armature inductance	No-load speed	Rated speed	Rated DC supply
	0.01 H	4000 rpm	2500 rpm	12 V
Mechanical	Rotor inertia		Rotor damping	
	$2000\ g\cdot cm^2$		$1e\text{-}06\ N\cdot m/(rad/s)$	

The output waveform representing the rotational speed response of the DC motor is presented in Figure 8. As expected, the motor runs at about 2000 rpm when the applied DC voltage is 2.5 V. In less than 10 seconds, the rotational speed of the DC motor reaches its steady-state value.

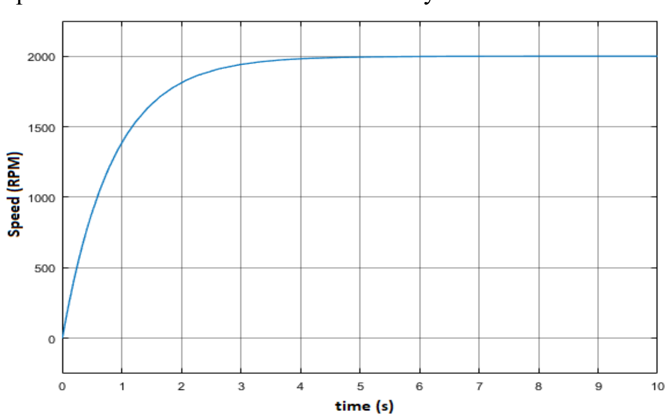

Fig. 8. Rotational speed response of the DC motor

III. ANALYSIS OF STUDENTS' PERFORMANCE

Besides incorporating our model-based approach through the use of MATLAB Simscape, we conducted a comparative analysis of students' performance. To do this, we collected the available data from past offerings of the course (Spring 2016 and Fall 2016) to compare with the Simscape-supplemented course (Spring 2017). We remark that the instructor used Multisim in Spring 2016 and Fall 2016. The raw data consisted of the students' exam scores for the three semesters that were compared; there were three exams given in each semester. We computed the means and standard deviations for each group of students, and the results are summarized in Table II. It is pointed out that the exam scores considered in our study were those of first time course takers in order to avoid skewing the results due to prior students' exposure to the course material.

TABLE II. STATISTICS FOR THREE SEMESTERS

		Spring 2016 ($n = 27$)[b]	Fall 2016 ($n = 21$)[b]	Spring 2017[a] ($n = 20$)[b]
Exam 1	Mean	74.44	66.90	78.00
	Std. Dev.	12.12	21.52	12.58
Exam 2	Mean	74.56	74.90	81.55
	Std. Dev.	15.08	16.93	20.09
Exam 3	Mean	73.52	73.67	72.10
	Std. Dev.	15.03	21.74	14.74

a. Term in which MATLAB Simscape was introduced
b. n denotes the number of students who took the exam

Based on the results presented in Table II, it appears that there is a slight improvement in students' performance as a group in the Spring 2017 offering, the semester in which Simscape was first introduced. The means of the exam scores for Spring 2017 are slightly higher than those for Spring 2016 and Fall 2016, with the exception of Exam 3 for Spring 2017 which is barely lower than the means obtained for the other two semesters. Our initial impression is that the incorporation of Simscape might have improved students' performance in the best case scenario; at least we have confirmation that the use of Simscape is not detrimental to students' performance.

To objectively assess whether there is a significant difference between the mean scores, we performed an ANOVA (analysis of variance) single factor test. This statistical test analyzes the data variability between and within groups to determine whether any of the differences between the means are statistically significant to a prespecified significance level (type I error). In our case, we set the significance level to α = 0.05 and obtained the following statistics: $F = 2.697$, $p = 0.075$, and $F_{crit} = 3.138$. Based on these statistics, we conclude that the null hypothesis that the means are equal cannot be rejected since $F_{crit} > F$, or $p > \alpha$. That is, our data do not show any statistically significant difference between the means observed in the three semesters that were compared.

In addition to exam scores, we analyzed the assessment results of students' learning outcomes. We framed these outcomes as course objectives. Only the course objectives that are relevant to the use of Simscape are presented in Table III. Once again, an ANOVA test performed on the data did not reveal any statistically significant difference in the assessment results for the three semesters that were observed.

TABLE III. ASSESSMENT OF STUDENTS' LEARNING OUTCOMES

Course Objective	Spring 2016	Fall 2016	Spring 2017[a]
Perform analysis of circuits containing diodes, including voltage reference circuits, rectifiers, and the Zener voltage regulator.	3.6	3.2	3.4
Analyze op-amp circuits such as inverting and non-inverting amplifiers.	4.7	4.0	4.4
Properly bias and analyze MOSFET and BJT transistors at DC.	4.4	4.5	4.5
Utilize modern engineering tools to design and model practical circuits relevant to the course.	4.0	4.1	4.1

a. Term in which MATLAB Simscape was introduced

To conduct the assessment of learning outcomes, the instructor selects an evaluation instrument (e.g., an exam problem, a homework exercise, etc.) that addresses a specific course objective, and then proceeds to score the performance of each student on a Likert scale from 1 to 5 (1 = very poor; 2 = poor; 3 = marginal; 4 = good; 5 = excellent). The figures that appear in Table III are the averages of those scores. The evaluation instruments that were selected in this study required a certain level of familiarity with Simscape in order for the students to complete their tasks, thereby allowing the instructor to determine the students' level of attainment of a particular course objective.

To complete our study, we also conducted a student survey to obtain their impressions about the effectiveness of the model-based approach at reinforcing conceptual understanding of the topics covered in the course. We designed a simple questionnaire and distributed to the students at the end of the Spring 2017 semester (all of the students who took the class responded to the survey). The survey consisted of six (6) questions containing statements which students had to rate in terms of their agreement or disagreement on a scale from 1 to 5 (1 = strongly disagree; 2 = disagree; 3 = neutral; 4 = agree; 5 = strongly agree). The means and medians of their responses were computed and are summarized in Table IV.

TABLE IV. SURVEY RESULTS

1 = strongly disagree 2 = disagree 3 = neutral 4 = agree 5 = strongly agree		
Statement	**Mean**	**Median**
1. I had prior exposure to specialized software (e.g., Matlab, LabVIEW, etc.) in other courses or training workshops.	3.95	4
2. Modeling and simulating electronic circuits with SimScape was relatively easy.	4.55	5
3. I can understand the role of modeling of electronic devices much better after having used SimScape.	4.45	4.5
4. The use of SimScape has helped me understand electronic circuits much better.	4.5	5
5. Acquiring modeling skills will improve my employability prospects.	4.65	5
6. I still prefer the more traditional approach to course instruction (solving electronic circuits with very little or no use of software).	2.6	2.5

It can be seen from Table IV that students view the use of Simscape favorably, as indicated by the responses to questions 2 through 5. Although most students had prior experience using other software, as indicated by the responses to question 1, the incorporation of a new tool such as Simscape did not impose an undue burden on students to meet the course objectives, as reflected by their positive responses. The students' perception is that the use of Simscape has had a positive effect in their learning experience. They express a better conceptual understanding of electronic devices and the models that describe their behavior in electronic circuits. Question 1 was included in the survey to learn about their exposure to specialized software in previous courses. We thought this might have had an effect on students' attitude toward incorporating Simscape into the course, given that students take the prerequisite courses from instructors with different teaching philosophies. In turn, this motivated us to ask question 6 to ascertain students' preferred instructional method, whether traditional or software-enhanced. In this respect, the survey shows that students are much more receptive to new instructional methods than they are to traditional methods.

It is worth mentioning that one student provided this comment: *"The use of this Software eases the comprehension of how circuits work. This makes us build it in a way where we get to understand complex problems in an easier way."*

IV. CONCLUSIONS

In this paper we gave an account of our experience in using MATLAB Simscape in an introductory electronics course. The tool allowed us to test a model-based approach to cover the contents of the course. To acquaint students with this teaching strategy and the tool itself, we developed four Simscape-based modules covering various electronic devices and circuits. We found that interspacing lectures with Simscape assignments enhanced the students' learning experience and elevated their level of engagement. In addition, we made a statistical analysis of students' performance using exam scores and compared them with those of past semesters in which Simscape was not introduced. Although the analysis revealed no significant statistical difference between the means of the semesters that were compared, the slight improvement in exam scores that we noticed, however marginal, is an encouraging development. The positive responses from the student survey reveal that students are receptive of the model-based approach and the use of Simscape.

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