Consumer Electronics Design as Preparation for Capstone Design

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***Abstract*—We present the results of modifications made to an undergraduate electrical engineering curriculum intended to resolve observed deficiencies in student mastery of design. Changes consisted of the implementation of a sizable design project in an electronics course taken a full calendar year prior to capstone project initiation. Both the scope of this design task and the temporal separation from the target of intended outcome improvement present a unique opportunity for examining the efficacy of this approach. We found substantial improvement in design outcomes; however, the benefits of these improvements were narrowly restricted to the deign topics presented in the earlier course design project, indicating a lesser overall impact on general design mastery.**

Keywords*—*design, capstone, senior project, engineering education

I. Introduction

Design, as an engineering task or outcome, is often limited to select courses in a customary engineering education experience. Ordinarily, the weight given to design is far greater in the last year of education, often culminating with a final capstone project. However, the task of learning design in preparation for a final capstone presents a variety of options for adjusting curricula to improve design outcomes. At Western Washington University we identified a deficiency in capstone design outcomes. This led us to explore options in the curriculum to correct lacking demonstrated student performance in design tasks. Ultimately, we selected the insertion of a sizable design task a full year prior to the start of the capstone design process. This option was chosen primarily for its minimal disruption to existing curricula; however, its novelty makes it an interesting candidate for evaluation of the efficacy of this approach on improving design performance in the later capstone project.

II. Background

A. *Project Based Design Education*

Although many examples of capstone design, integration of design into engineering curricula, and observations of design instruction methodology can be found in literature, the work described herein focuses on project based learning (PBL) approaches to design instruction. This is due primarily to the heavy established focus on PBL in the curriculum at Western Washington University's electrical engineering program. Within this subset of design education focus, most existing research falls roughly into categories of design pedagogy examined by Wood and Otto [1]–[3]. Central to the approach by Wood and Otto is the concept of design starting with investigation of existing designs and following a decision-making process of design by redesign, choosing parametric, adaptive, or original redesign as deemed prudent. Advanced design in this approach is front-loaded by way of the initial investigation of completed, existing designs. The major design focus left out of this body of work is more traditional methods of design focusing on the sequential expansion of design scope [4]–[6]. Although within these works lies several elements for instructional consideration, including optimization of active learning, such considerations are not captured in the work described herein. Rather, we focus consideration on the scope, structure, timing, complexity, and cyclicality of design tasks.

A more traditional approach to teaching design focuses on an incremental process where design tasks are progressively scaled up in both scope and difficulty, generally with cyclicality (reflection on the outcome of the design and consideration of redesign) ignored, often until the final capstone project. The idea behind this approach is that students "must first learn to crawl before they can walk or run." [4] While the fundamental nature of engineering education through sequential learning remains universally-accepted by education researchers, some are more supportive of introducing students to very complex designs, perhaps more complex even than their capstone expectations, through reverse engineering [1], [2]. The idea behind this approach is to expose students to the end of a design cycle – the culmination of all the processes they are preparing to undertake – prior to beginning a subsequent design cycle based on those observations. This redesign approach emphasizes the importance of reflection as part of the design process, as well as rejection of prior ideation. Still other approaches to design project introduction include sprinkling miniature design tasks with varying scope, complexity, and cyclicality, throughout the curriculum [3], [7]. Novel approaches such as this often include novel caveats. A common requirement for implementing miniature designs or "designettes" is structuring the design task such that it is limited enough that students focus on the process of design rather that becoming preoccupied with approaches to achieving broad objectives [8].

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B. Western Washington University Electrical Engineering Program Overview

The electrical engineering program at Western Washington University follows a structure common for ABET-accredited electrical engineering programs. The degree program has concentration options for majors in either embedded systems or energy systems with small (five course) variation between the two. Students apply for acceptance into the program in the Fall quarter of their Sophomore year, and nearly all major-specific courses are contained within their Sophomore, Junior, and Senior years. Major courses are only offered once per year, resulting in a rigid sequence of instruction even where outcome inheritance is not established by prerequisites. This is of particular interest to this study, as this structure ensures the cohort evaluated at the point of capstone design had a nearly identical educational experience through prior courses with design content.

As is becoming increasingly common [9], the capstone design course at Western Washington University spans a full academic year, with quarters of instruction covering planning, hardware design, and software design in order.

C. Capstone Design Project Planning

The capstone project consists of students working either alone or in a team of two. Each student/group has substantial leeway to select a unique project, with many students electing to work with a sponsor/client. All students are required to generate a project proposal which describes the goal of the project, the target users, and the anticipated benefits. Students must define all project requirements and constraints (with each requirement and constraint proved upon completion of the capstone design). Students are also required to identify project impacts and responsibilities. Alongside the generation of their project proposal, students work through a process of ideation and examination of existing technologies. This is similar to common reverse engineering design practices, except that the primary goal of the examination of existing designs is to establish necessary and sufficient design requirements and constraints rather than as a tool primarily for redesign. Subsequent quarters of design are split into hardware and software designs, the goal through each quarter being to meet the project requirements and constraints. Students are allowed to modify their project requirements and restraints, but to do so must submit formal change orders. Change orders are only approved if the change better meets the project goals and are not allowed to be used to simplify the goals of the project or bypass design difficulties.

D. Justification for instructional modification and evaluation

For the academic year 2015-2016, the senior design course sequence was modified to add a dedicated quarter focusing on hardware design. Commensurate with this change, requirements for embedded systems concentration students were expanded to include a fully-custom printed circuit board design including the following minimum elements: power regulation, microcontroller, sensing, and communication.

The first year of revised capstone implementation, most students failed to produce a design that met all hardware requirements. While no clear cause of failure was evident, students struggled to achieve design goals without an untenable number of design iterations. This often resulted in too little time to complete subsequent software implementations with fully-functional hardware designs. Indicators pointed to a general failure in design competency, specifically related to hardware design. Upon subsequent course review, the decision was made to implement design elements mimicking capstone design earlier in the curriculum. An advanced electronics course was selected as a candidate course for project based design implementation due to the strong overlap between electronics and capstone instructional topics, as well as the existing use of a course project in the electronics class. Replacement of the course project with a more involved design component required only minor modification to the overall electronics course structure.

III. DESIGN PROJECT COMPOSITION

A. Course Composition

The course chosen for design project incorporation was "Electronics II." This course is mandatory for all electrical engineering majors, and is delivered in the Fall quarter of the Junior year of the curriculum. Many of the course topics listed in Table 1 are directly applicable to capstone hardware design. The course includes ten weeks of instruction with three hours of lecture and two hours of laboratory each week.

TABLE I. ELECTRONICS II COURSE CONTENT

Topic	*Topic Description*
Op-Amp Design	Op-Amp design with resistive elements, integrators, differentiators. Static op-amp limitations. Dynamic op-amp limitations
Amplifier Circuits	Class A, B, AB, D
Regulators	Linear regulators, buck, boost, buck-boost, flyback, Cuk, charge regulators
Project	Class project integrating course topics as determined prudent by instructor

B. Design Project Composition

The new design project was selected taking three major elements into consideration:

1. Design exercises students engage in early in their education tend to stick with them into their capstone. A project with elements closely related to those elements common to capstone projects could ease transition to more challenging and open-ended senior projects [7].
2. The design should include an element of design reflection, ideation rejection, and ideation [1], [10]. Given the time constraints for the course project, a redesign of an external design reference should serve as the basis for evaluation of a prior deign.
3. The project should be composed of multiple small design tasks corresponding to each circuit element, with "scaffolding" [11] both through explicit design requirements as well as reference design reverse-engineering to maintain a focus on design and

optimizing topic and design process overlap between Electronics II instruction and capstone instruction.

With these considerations in mind, a candidate design requirement to build a USB-rechargeable headphone amplifier was selected. This design task not only includes substantial sub-design modules with a design process representative of subsequent capstone project module development, but also does an excellent job of meeting the needs of the Electronics II course. The reverse engineered example design was the Cmoy headphone amplifier [12]. This reference design does not meet the design requirements but provides an excellent point of reference to evaluate a previous design process's capability and suitability. Reliance on this reference design allows students to iterate based on those reverse-engineering observations.

The design requirements for the electronics project were stated as follows:

You must design and implement a USB-rechargeable headphone amplifier. The amplifier must have a USB-micro input that does not draw more than 500 mA of current. The amplifier must have one standard 3.5 mm audio jack to receive incoming line-level audio, and one 3.5 mm audio jack to output the amplified audio signal. The amplifier must have a rotary dial that adjusts the signal gain between 0 and 11 V/V with a minimum output current capability of 20 mA across the entire attenuation/gain range. Your amplifier must be capable of operation using a rechargeable battery, and the battery must be capable of charging via the USB power connector. The amplifier must function seamlessly when connecting and disconnecting the USB power source and must charge the battery upon connection to a USB power source without interruption to the functionality of the amplifier. The amplifier must have a mechanism to turn amplification on or off, and must indicate the status of powered amplification with a lighted indicator. The amplifier must also indicate charge status (a minimum of charging/complete) using a lighted indicator. Your design should minimize total harmonic distortion (THD) and your final product will be judged in part on its demonstrated THD.

A comparison of the design elements indicating shared design components for the reverse-engineered reference design, the electronics design project, and the capstone design project is show in Fig. 1. The applicability of identifying these design module relationships is to compare module topics for later evaluation of outcome improvement where we categorize design deficiencies both by topic and by deficiency type. Examination of changes in the degree of overlap between reference, electronics course, and capstone designs are beyond the scope of this investigation, but would make for an interesting future investigation.

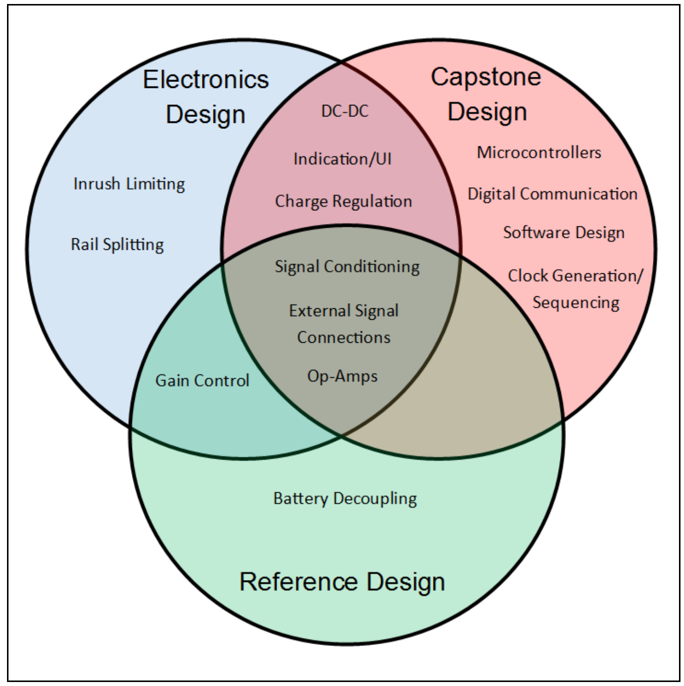

Fig. 1. Comparison of common design modules in the reverse engineered reference design, the electronics design project, and the capstone project.

The goal of the electronics design project was to allow students to complete a full consumer electronics design and produce a final design "totem" which serves as a milestone of their accomplishment and a point of reference for demonstration of their own design ability [13]. However, within the taxonomy of design tasks – system, component, and process – the goal was not to require a complete system-level design. Along with specific and detailed requirements which largely defined the required design elements, the students were also provided with a printed circuit board (PCB) platform to use as the basis for their project development.

The PCB enables students to use common surface mount components without needing a collection of separate breakout boards. This also includes footprints for common design elements whose part selections were made both for the practical implementation of the project as well as to keep student's focus on the core design processes. Common components used in every design were: a dual-gang potentiometer (Bourns), a surface-mount right-angle slide switch (C&K), and dual stereo 3.5 mm audio jacks (CUI). Generic footprints for common deices (inductors, capacitors, LEDs, etc.) were also included on the project board, but did not limit students to any particular circuit configuration.

The board limited students to two SOT23-5 footprints and one SOT23-6 IC footprint, although as indicated in Fig. 2, the board included 12 rows of DIP-compatible breadboard space on which students could affix additional breakout boards. As much as was feasible, the board left all interconnections between components open, maximizing the ability of students to produce a novel design.

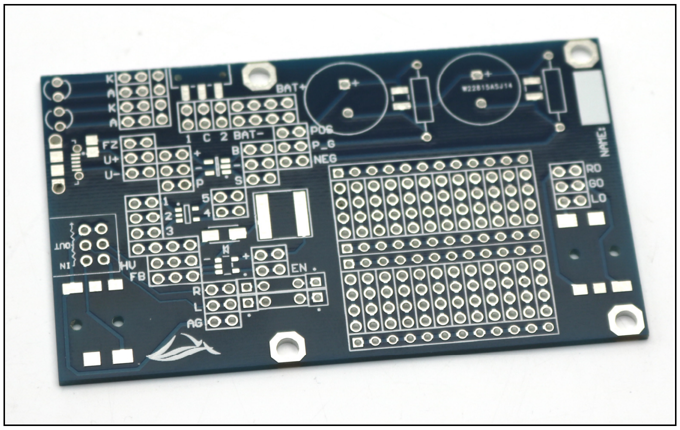

Fig. 2. Project development board used for the new design project. A blend of breakout footprints for common surface mount components and general purpose breadboard arrays allows students to implement their design without needing to create a custom circuit board and without using a collection of separate breakout boards.

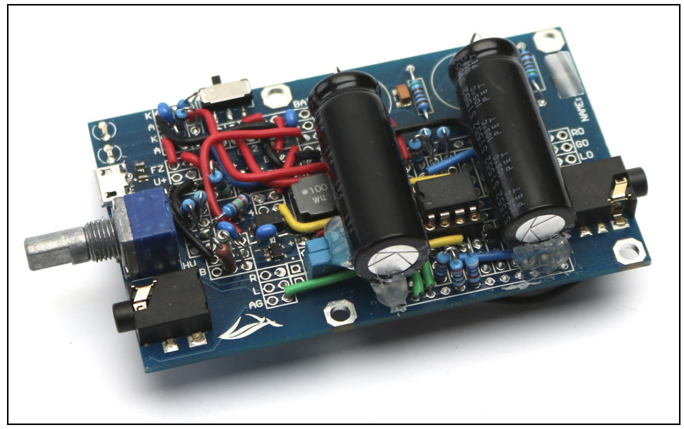

Fig. 3. An example completeted headphone amplifier design on the development board of Fig. 2. The design blends implementation with surface mount components as well as through-hole components and jumper wires. The final desisn is completely soldered with the exception of a socket-connected DIP-8 operational amplifier, allowing different amplifiers to be tested to verify harmonic distortion with different quality amplifiers.

IV. Design Project Implementation

The new design project was implemented in the Electronics II course in the Fall quarter of 2016. Initial reverse-engineering began during week five of the quarter with ideation, development, and testing cycles occurring during weeks six through ten. Student designs generally settled on five core design modules, each of which followed a distinct design process of repeated ideation, development, and testing. The five primary categories were:

- Charge regulation
- DC-DC conversion
    - Rail splitting (if using a single output DC-DC converter)
- Signal conditioning
- Gain control
- Indication

Many students also included in their design other elements which, while not necessary by the project requirements, improved the overall design's suitability as a consumer electronics product. Among the most common optional elements were battery undervoltage protection and battery inrush current control.

Overall performance on the design project was excellent, with 88% of students (n = 26) successfully implementing a final design that met all requirements. An example image of a completed design is shown in Fig. 3. Students were given the ability to, upon completion of a successful product development, implement their solution using a custom PCB. An example of one such design is shown in Fig. 4. However, for the cohort examined herein, only two students opted to complete a final custom PCB design.

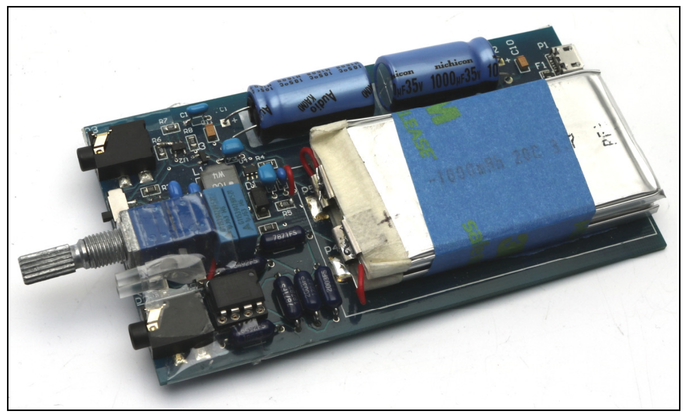

Fig. 4. An example of a student who implemented their final audio amplifier product design using a custom circuit board following successful product performance on the template prototyping board of Fig. 2.

V. Evaluation

To assess the efficacy of the new design project implementation, a methodology for collecting and categorizing data was developed and then applied to the Winter 2017 Senior Design class. Because the Electronics II course in which the new deign project was implemented was a Junior-level course, it was possible to implement the course project in Spring 2016, then evaluate capstone performance of the Senior class in Winter 2017 as a control study, followed by identical observation of the Winter 2018 Senior class capstone performance to identify any changes in design performance.

A. *Assessment Methodology*

We developed an assessment methodology that would capture failures encountered throughout design process rather than examining course outcomes alone. Although failure is an essential part of the design process, the utility of failure should be maximized in design to reduce overall design time and design cycle iterations. We wanted to ensure an assessment methodology that captured failures that managed to persist through multiple design iterations.

For the Winter 2017 and Winter 2018 hardware design capstone course, we cataloged every failure identified by project groups. These failures were binned based on both the design element in which the failure occurred, as well as the stage in the design cycle in which the failure occurred. Design cycle stages were divided into three broad categories: ideation, implementation, and verification. Failures of ideation refer to design concepts for which no amount of development will ever achieve a result that meets design requirements. For instance, students whose design implements communication between four devices using UART serial protocol, which is fundamentally only capable of communication between two devices. Failures of implementation are the most common and refer to incorrect application of engineering knowledge to a design solution. For instance, if a student's design implements a buck regulator operating at 2 MHz but the student does not select a high-speed diode for the design. Failures of verification are failures which are not corrected by the verification process. For instance, in the aforementioned example of the non-high-speed diode, if that error existed in a design iteration, but during verification students identified a different error and failed to evaluate the remaining design elements, the failure would persist to another design iteration. That failure to utilize the verification process to correct the error would be considered an additional failure. In this manner, a single point of failure may be reflected as multiple failures if it persists across more than one design cycle and identification was possible during the verification design phase.

Failure binning based on design elements allowed for identification of failure as it corresponds to design topics covered in the earlier electronics design project versus failures related to design elements not covered by the prior design experience. Descriptions of the identified design element bins are listed in Table 2.

TABLE II. CAPSTONE DESIGN PROJECT ELEMENTS

Element	***Element Description***
Regulation	Aspects related to power regulation including AC-DC and DC-DC transformers, virtual grounds, and voltage references.
Computation	IC elements performing computational functions such as microcontrollers.
Sensing	Elements participating in sensing including transducers and ICs performing analog and digital sensing acquisition.
Analog	Circuit elements modifying analog signals including filtering, offset adjustment, and other signal conditioning.
Communication	Digital communication, including wired and wireless methods.
Timing	Mostly referring to clock signal generation and reference frequency generation, this category also includes sequencers.
Steric	All elements of mechanical design and "fitment." This category takes into account the need for three-dimensional design.

VI. RESULTS

Both the 2017 (control) and 2018 senior design cohorts had nearly identical numbers of students included in this evaluation. In 2018 there were 17 students with 3 working solo. In 2017 there were 17 students with 9 working solo. However, the rate of errors per group remained proportional to the size of the group, with student groups (of two) averaging 92% more errors than solo students in 2017 and 106% more errors in 2018. Due to this convenient balance in student population and error distribution, results are presented as raw numbers initially, with fractional composition presented in later data.

Shown in Fig. 5, the 2018 cohort that underwent an electronics design project during the prior academic year showed a notable reduction in overall error count, with the largest differences in ideation and implementation. Overall there were a total of 94 documented design failures in the 2017 control cohort (without the prior year design experience, henceforth referred to as the non-design cohort) and 67 documented design failures in the 2018 cohort (with the prior year design experience, henceforth referred to as the design cohort).

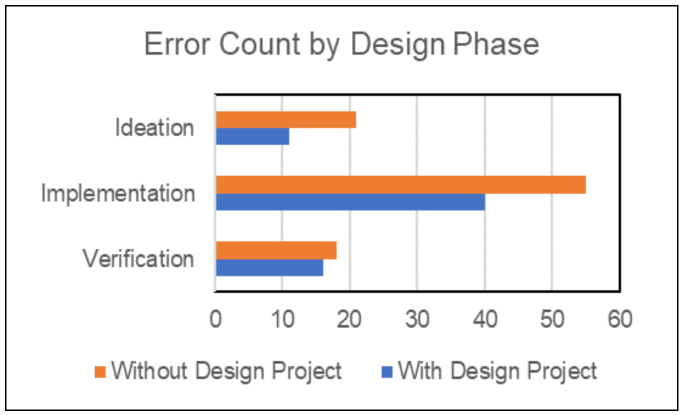

Fig. 5. Comparision of observed design errors examining a capstone project hardware design phase for cohorts who underwent an electronics design project versus those who did not have the electronics design project.

From Fig. 6 we see the differences in observed error counts across the various project elements. By count, the design categories with the greatest reduction in failure count were regulation and analog. Fig. 7 present the same date shown in Fig. 6 but as a fractional composition of the overall error for each cohort. The addition of the design project for the latter cohort resulted in a shift in the error composition away from regulation, timing, and analog towards steric, and computation.

Overall failure rates for individual students and groups was weakly correlated with successful project completion. Across both years, students and groups who failed to successfully complete their capstone project had 121% more errors per student than students and groups who successfully completed their projects. However, there was substantial variability in error counts observed per group, with unproductive groups able to fail to produce a successful project with very few design iterations and errors, while other more productive groups were able to successfully complete their project despite substantial error counts and design iterations. The weak association between student/group success and failure rate could in part be due to the tendency of advanced students to challenge themselves with more complex projects and design requirements.

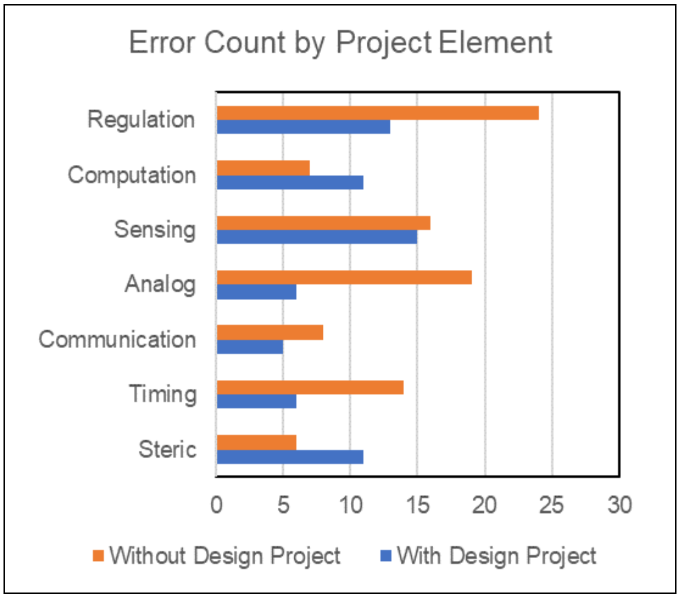

Fig. 6. Comparision of observed design errors binned by project element.

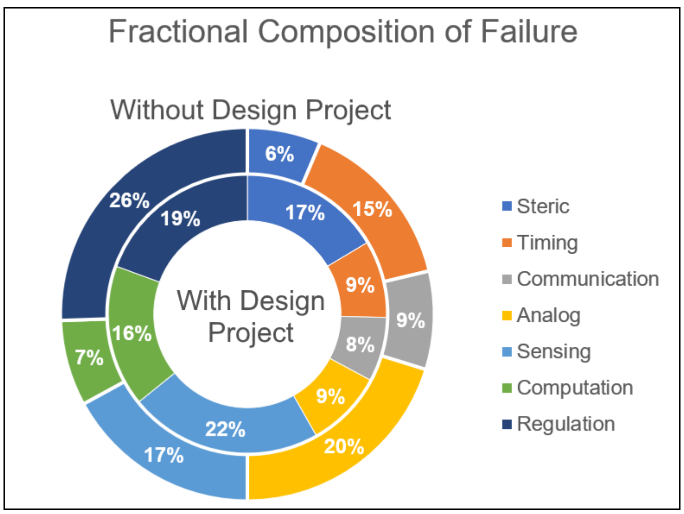

Fig. 7. Fractional composition of failure by project element. The inner doughnut is relative error fractions for the design cohort and the outer doughnut represent the relative error fractions for the non-design cohort (control).

VII. Discussion and Conclusion

The data results indicate a notable reduction in design process errors when comparing the design cohort with the non-design cohort. Although the failure count reduced from 94 to 67, that reduction was not evenly distributed across project elements. The largest reductions in failure came from the analog and regulation project elements. It is notable that these are the two capstone project elements that have the most overlap with the prior electronics course project as illustrated in Fig. 1. These two categories alone accounted for 22 of the 27 count error reduction. One area with a clear failure rate increase was steric failures. Although the cause of this change is difficult to pinpoint with certainty, several projects in the later 2018 design cohort included interactions with mains electric power, and the vast majority of steric failures were due to improper accommodation for either the bulky geometry of mains power plugs, or a lack of consideration for the housing clearances needed to chassis-mount such connectors.

In addition to the unequal distribution of failure improvement across project elements, when comparing improvements by design phase we see almost no improvement in the verification design phase. This is another indicator suggesting general mastery of the design process was not the primary benefit of the added design project.

The goal of this exercise was to improve high failure rate in capstone design by implementing a consumer electronics design project much earlier in the curriculum. While a notable improvement is visible in objective data analysis, that improvement was not distributed across either the design process or the various capstone project elements which make up the larger overall design. Although the aim was to promote mastery of design, it is possible the exercise also (and perhaps more so) improved understanding of the operation of common elements of embedded systems. There does not appear to be any obvious mechanism to retroactively identify the degree to which the improved design experience was the result of design process mastery or engineering tool mastery.

One potential modification to curriculum, based on these results, may be to ensure more project elements common to capstone design are incorporated into design tasks earlier in the curriculum. Examining Fig. 1, that would mean implementing a design task (or multiple design tasks) with substantially more overlap with the capstone design. One way of looking at this observation is as a point in favor of implementation of "designettes" distributed throughout the curriculum which incorporate engineering tools and methods as such knowledge is acquired. However, this suggests further questioning and evaluating the degree to which small design tasks throughout the curriculum are truly imparting an understanding of design, or merely reinforcing mastery of the underlying engineering tools and techniques. There may not be substantial distinction between these two areas of mastery, as competency in design builds competency in the application of engineering concepts, and mastery of engineering concepts enhances design.

While this study focused on an embedded systems design for electrical engineering majors, it provides insights more generally into the efficacy of corrective measures to remedy capstone design failures. Moreover, it suggests the importance of examining not only broad outcome attainment related to design, but also to more closely examine how design success is distributed across sub-design tasks that form the universal building blocks of capstone design projects that are broad in scope.

Acknowledgment

The authors would like to thank Reza Afshari and Andrew Syltebo for their contributions to the production of this manuscript as well as their assistance with the development and implementation of the design project described herein.

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