

Using Failure to Teach Design

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Abstract

Learning from failure during large ill-defined design projects provides students with opportunities to practice their abilities to explore other solutions, demonstrate that a required feature may violate physics, and propose design changes. This learning requires students to embrace their failures, something they have been trained to avoid in the past. This paper presents a case study where design students were encouraged to discuss failure in the context of design loops using reflection journaling and continuously evolving design requirements.

Introduction

Success of undergraduate engineering design projects can be measured in many ways, from quality of learning, to ability to engage in teamwork, to completion of all technical details specified at the onset. While Twin Cities Engineering (TCE) students show a range of development and were able to meet programmatic outcomes, only one of 13 design teams in the last three semesters has completely met all measures of success. The faculty's perceptions of this low success rate was that students were failing to even fail. That is, students failed to take action on the key components of their designs. For example, student teams tried to minimize the chance that something would go wrong in the design by computing every conceivable calculation, focusing on the technical requirements rather than the breadth of expectations in design. As novice designers, they typically failed to consider the design problem from all angles and to determine all relevant information. As a result, when the team finally did attempt to put their hard work into action, they would inevitably come up short and thus fail without ever really engaging in much actual design work. This case study presents a description of an intervention intended to reduce the barriers to action-based failure, increase the reward for action-based failure, and make visible the hidden failure of inaction.

The next section overviews the relevant literature. This is followed by a section describing the TCE program, and the managing design through failure intervention (MDTFI). These sections are followed by a description of the methodology used to conduct this case study. Then, the findings for the case study are presented with anecdotes that reveal as much as possible about projects and the process without violating nondisclosure agreements. Finally, conclusions and implications for future research and practice are discussed.

Review of Literature

ABET describes engineering design as “a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.”¹

Although engineering designs may occasionally be completed without error on the first attempt, it is a rare event even for relatively simple designs. The need for iteration implies that at some point in the process things did not go perfectly. Yet, none of the well-accepted texts reviewed by the authors^{2,3,4,5,6} discussed iterative failure or how to incorporate it into the design process.

Rather, when failure is discussed, prospective engineers are often bombarded with examples of dramatic catastrophes that serve as warnings. For example, the Tacoma Narrows Bridge, the space shuttle Challenger, and the Hyatt Regency Hotel Kansas City walkway are all used to warn budding engineers away from undesired behavior⁵.

There are a group of books that discuss the positive outcomes that result from failure^{7, 8, 9}. However, these books focus more on the learning associated with catastrophic or potentially catastrophic failures than from the learning involved in prototyping and refining.

Another form of failure discussed in the engineering lore appears to have evolved in the late 1990s through the 2000s. It involves venture capitalists using the mantra “fail fast, fail often” with the idea that most startups will not be successful. Thus, the sooner they fail, the faster they can be abandoned, making resources available for other opportunities. Such strong use of the word failure in this context is likely a poor extrapolation¹⁰ and is already falling out of favor^{11, 12}.

Yet another type of legendary engineering failure is to snatch victory from defeat by repurposing a “failed” design. The classic case studies for this mode (regardless of the accuracy of the tales) are Post-it Notes¹³ and Teflon^{TM14}.

A final, and most pervasive type of failure described in engineering, has only one common legend. It is that of Thomas Edison who developed, as examples, an effective lightbulb and an improved battery¹⁵. In the case of the lightbulb, Edison did not invent the technology, but rather refined it through many iterations, eventually arriving at a model that met his design requirements¹⁶. This process resulted in several patents for various electric lights, lamps, or filaments (see for examples^{16, 17, 18, 19, 20}). These inventions are only a few of the documented iterations that Edison and his staff conducted²¹. In the case of the battery, Edison conducted thousands of iterations to develop a technology that was superior to the state of the art of the day. He began producing these batteries, but pulled them from the market to continue improvements. After many more design iterations, he returned to the market with a product that was as superior to his original as the original was to the existing technology¹⁵. Edison’s competitor, Nikola Tesla, also performed iterative design. He claimed “When I get an idea I start at once building it up in my imagination. I change the construction, make improvements and operate the device in my mind. . . In this way I am able to rapidly develop a perfect conception without touching anything.”²²

The design process in engineering is often discussed as iterative processes in books on the subject^{4, 5, 6}. In many cases, the iteration is discussed as an aside^{4, 6}. In one text, the design iterations is a central theme, but refers to the evolution of products in the market rather than iterations of prototypes during development⁵. All reviewed books present a design matrix as if many product concepts were being developed in parallel^{2, 3, 4, 5, 6}, which is interesting given that economic analysis shows that it is generally best to focus only on the design most likely to be successful²³.

One area where the idea of failure and the economics of iterative loops is so pervasive that it is strongly embraced by everyone in the community is software development. Programmers expect that code will not compile, compiled code will not run, and running code will not produce correct

results until many bugs have been worked out. Fortunately for programmers, the cost of compiling and executing code is very low, which means that many iterations can be done quickly and efficiently. Shifting the focus from formal development processes to strategies that exploit the ability to rapidly iterate has led to the development of the agile software development movement²⁴. Much effort has gone into developing optimal procedures for designing, writing, and deploying software (see for example^{23, 25, 26}). The key concepts in agile development are rapid design cycles, iterative improvement, and collaboration with the customer^{26, 27}. Key economic differences have also been identified that influence the optimal iteration rate. Generally, the larger the cost of executing a decision making loop, the less frequently iterations can be done²³. One implementation of this design philosophy applied in the context of product development, rather than software development, is the Toyota Product Development System²⁸. Agile methods have also been used at KTH, The Royal Institute of Technology as part of their Mechatronics curriculum²⁹.

In summary, engineering design is an iterative decision making process. Because the need for iteration implies that at some point in the process things do not go perfectly, information is needed on how to provide instruction in engineering design curriculum that takes into account the possibility/probability of failures. Such instruction could include failures in design, the positive consequences of failure, and how to incorporate it into the design process. Unfortunately, the literature contains little useful information in this area.

Description of the Twin Cities Engineering Program

TCE is one of two engineering programs in the Department of Integrated Engineering of Minnesota State University, Mankato. The other program is Iron Range Engineering (IRE). They are both upper division programs meaning students are rising juniors predominantly from partnering community colleges. IRE grew out of a need to train engineers in the iron range of northern Minnesota. Physically located at the Mesabi Range Technical and Community College in 2010, it was designed to meet the Accreditation Board of Engineering and Technology criteria¹ with a project-based curriculum (PBL)³⁰. The core philosophy and curriculum was replicated at TCE in 2013 with two full-time faculty, a part-time industrial relations coordinator who also serves as adjunct faculty, and a technical writing graduate assistant. Additionally, the program uses industry mentors to support students as they work toward completing their projects.

TCE students are required to complete four semester-long design projects before graduation. Each of the four design projects is completed by a team comprised of three to five students. Project deliverables, specified by the project sponsor, may include a prototype, a procedure, test results, a final document, or other evidence. Each semester, students receive credit for working on their projects in two three-credit hour courses. The first course, called Design, represents most of the actual design work associated with the project. The second course, called Professionalism, represents much of the work associated with professional development in a range of areas including communication, teamwork and personal and professional responsibility. Students move through a sequence of four Design and four Professionalism courses before graduating, working on a team design project each semester they are registered for the pair of courses.

In the design course, each student team submitted an executive summary with design specifications and measurements to show how well the design met the specifications. This assignment was used to assess the ability of the design project to meet specifications. In the professionalism course, each student team submitted a final design report for the same project. This assignment was used to assess the quality of communication about the project. The lines between these two courses were indistinct and often the same thing was assessed in both courses from different perspectives. A one credit seminar course meets weekly to provide the stage for discussing topics related to design and professionalism. Typical topics include, but are not limited to, technical communication, design processes, interview skills, leadership, metacognition, learning strategies, and ethics.

As part of their design grade prior to the intervention, students had been required to submit three design concepts with evaluations. The intent was for students to create a design matrix as suggested in Pugh⁴. In practice, the faculty observed students implementing this assignment by developing one idea, creating minor changes, and performing an assessment that was skewed to result in the selection of their preferred design. Often this was the first design that the student team developed. When the students attempt to implement the design, they get feedback in the form of assessments from faculty, experiments they perform, and client corrections. The assessments from faculty are often based on intuition and wisdom which allow them to predict with some success the outcomes of the experiments the students perform. Regardless of the predictions of the faculty and the students, the actual outcome of the experiments dictate next steps. Either the design works, or it does not. If it does not, which is most often the case, at this point in the semester there is little to no time for recovery. Finally, as a design comes together the client(s) may provide feedback that the students did not appropriately frame the problem (i.e. the design is doing what was asked, but this is not what is needed) or that the design team misinterpreted the problem (i.e. the design is not doing what was asked). It is also possible that the needs changed during the course of the design (i.e. the design would have been useful in the past but something else is needed now)²³. The program faculty have observed the first two of these three forms of feedback and suspect that the relatively short time line of one semester greatly mitigates the third issue.

In addition to the seven credit hours described above, students also participate in multiple technical competencies each semester. These competencies are one-hour courses associated with a technical topic. Six core competencies from mechanical engineering, six core competencies from electrical engineering, and four general core competencies are required. The six mechanical core competencies are dynamic systems, manufacturing processes, material science, mechanics of materials, thermodynamics, and fluid mechanics. The six electrical technical competencies are instrumentation, AC circuits, signals and systems, electronics, digital logic, and electric machines. The four general core competencies are statistics, either programming or mathematical modeling, engineering economics, and entrepreneurship. Fourteen additional advanced competencies, which may be extensions of those already listed, are also required. The core competencies are intended to provide a breadth of exposure plus depth in a specific area of a topic. The breadth is provided through learning conversations (where technical content is discussed and students are expected to be active participants), readings, close-ended homework, and similar activities. The depth is provided by a deep learning activity (DLA) which is an open-ended problem defined by the student and approved by the faculty. As examples, a DLA could

involve choosing, designing, and executing an experiment to determine a material property, designing a filter to meet certain specifications, or researching a topic of particular interest. Ideally the DLAs are connected to the students' design projects in some way and, in this way, the DLA supports a design project. An example of such DLA support was a student who studied and calibrated a laser positioning sensor for an application where the surface being detected was in fluid as an Instrumentation DLA. In this example, the team design project was to design a system to measure a media under various fluid flow conditions.

The Managing Design Through Failure Intervention (MDTFI)

The intervention was designed to address the faculty concern that many student teams were unsuccessful in completing the final technical outcome of their design projects. For example, faculty observed that student teams would put a lot of time and energy attempting to perfect their design on paper based on assumptions about invalid (or unworkable) sub-designs and components. Thus, the project was doomed to failure from the moment the first bad assumption was made. Another example that frequently occurred was that students misinterpreted the needs of the client. In this case, the students have effectively failed without even starting. In both examples, had the teams performed initial work like fabricating mockups, testing components, reaffirming their understanding of client needs through technical memos, or building prototypes to test their assumptions and understanding rather than pressing on with misinformation, they could have course corrected early and ended the semester with a successful project, rather than just the experience of a design cycle with deadlines and communication benchmarks.

The MDTFI explored the embracement of failure within the context of instructing undergraduate engineering design. To implement the intervention, several changes were made in TCE's design, professionalism, and seminar courses. First, faculty actively strove to help the students embrace failure. Second, students on each design team were required to weekly record both completed tasks from the previous week and planned tasks for the next week. Finally, students were allowed to evolve the requirements of their project as a function of time. These interventions differ from traditional approaches where failure is often discussed as something to avoid, teams create detailed Gantt charts early in a project but fail to adhere to or update the schedule, and project specifications are established in stone soon after the commencement of the project.

Faculty encouraged an open discussion of failure in several ways including dedicating seminar time to discussing the economics of iterative decision-making loops²³ in design and starting each seminar with "Five Minutes of Failure" (5oF) where student teams were enticed by a small cash prize to present their biggest learning from a failure in the past week. The faculty also presented an economic framework for design decision-making. This framework focused on a few key concepts: perishability, buffering (holding cost and transaction cost), and the optimal ordering of risky components with associated costs. The implementation of this was done in the context of Col. John Boyd's observe, orient, decide, act (OODA) loop²³. Perishability and risk are the reasons the design specifications were allowed to change as a function of time. Perishability refers to an opportunity that has a maximum economic benefit at some point in time. If a project is forced into a specification set early and the needs of the client change, the project may be perceived as a failure even if it successfully meets all of the specifications. By contrast, if the specifications are allowed to evolve, the changing needs of the client can be addressed in real

time by regularly checking in with the client to ensure alignment between current needs and current direction. The tree swing cartoon, a version of which appears in Total Quality Management and Operational Excellence by J. Oakland in 2014 provides graphics that depict various perspectives of a tire swing including how the customer explained it, how the project leader understood it, how the engineer designed it, and how the sales executive described it³¹.

The second, and more important reason for allowing the students to evolve requirements was to encourage them to apply the economic framework described above and attack low-cost, high-risk components of the design first. The faculty had observed that usually students attack the lowest risk components of a design first to get some success under their belts even though a later failure would require substantial rework of these components. By avoiding the high-risk design activities, students were pushing the risk of failure to the end of the semester when it was too late to recover. By embracing the possibility of failure and working on the high-risk components first, students have time to recover from failures or time to change the direction of the project if they are attempting the impossible. Students were encouraged to estimate the risk of each part of their design and attack the high-risk components first. If the components were easier than expected, the team could expand their project and accomplished more than they had originally set out to do. If they were unable to successfully complete the high-risk components, then they were at a minimum able to search for other solutions or discuss the issues with the client. Thus, the logic in allowing the students to evolve the design criteria was to encourage them to attack the high-risk components early.

To facilitate students taking action and eliminating risk, the MDTFI provided student teams with opportunities to change their deliverables throughout the semester. Specifically, the students were asked to “create a weekly task with tracked progress and an updated set of final project deliverables and constraints.” In addition to facilitating students taking action and eliminating risks, the progress update was designed to help students identify the low-cost, high-impact tasks in the design project. The students were assessed on four aspects each week: status of prior tasks, new tasks with ownership, an update to constraints, and an update to deliverables. Updates to constraints and deliverables had to be justified. These weekly documents were required starting in the third week of the semester and ending two weeks before the project due date when the design requirements were finalized. Rather than being large difficult assignments these documents were designed to be both rapidly created and rapidly assessed.

Methodology & Research Question

This exploratory study relied on case study methodology. A case study is an in-depth inquiry into a specific complex phenomena, which is set in a real-world context³². Merriam noted that a case study is used to gain in-depth understanding of the situation and meaning from those who are involved³³. A case study is a description and analysis of a single unit. According to Yin³⁴, case study design includes the research question(s), the unit(s) of analysis, the propositions, a determination of how the data are linked to the propositions, and criteria to interpret the findings. These topics are addressed in the following sections.

The research question for this case study was: How did the implementation of the managing design through failure intervention (MDTFI) affect student learning and success in the design

courses at the TCE program of the Department of Integrated Engineering of Minnesota State Mankato?

Unit of Analysis

The unit of analysis for this case study was the MDTFI that was implemented in TCE design projects conducted during the Fall 2015 semester with twenty-one students working on five projects. Implementing MDTFI involved obtaining support from the program chair and modifying two course syllabi and the seminar. The faculty discussed the intervention with the Program Chair and easily obtained her support for the change. The syllabus for the Design course was modified from previous semesters to require each team to provide weekly documents that tracked progress and proposed changes to the design specifications. In prior semesters, students in the Professionalism course had been required to reflect on several design experiences. For this study, the students were required to reflect specifically on the use of iterative loops as part of the design process. The Seminar course was modified to provide a venue to discuss failure, iterative loops, and the design process.

Propositions and Process for Linking Data to Purpose

Yin³⁴ noted that exploratory studies could state a purpose and the criteria for judging the exploration successful instead of propositions. In this exploratory case, the study purpose was to understand how the MDTFI affected student learning and success. The process for linking data to purpose was that the program's two faculty members individually monitored the intervention as it was being implemented and noted what was happening, what was working, and what could be improved. Then, the faculty members met to discuss and co-interpret their individual findings. The faculty members also reviewed and reported a table of the summative evaluation at the end of the semester that showed the design success and failure rate, both mitigated and unmitigated, of design projects.

Criteria Used to Interpret Findings

The criterion for interpreting this case is that it openly reports the reflections of faculty, thus enabling the readers to gain understanding of the complexity of implementing and understanding a MDTFI. The authors relied on investigator triangulation and their emphasis on repeatedly checking data accuracy and interpretations increased the trustworthiness of the data³⁵. The faculty also considered rival explanations for MDTFI outcomes. These are included in the faculty reflections.

Description of the Implementation of the MDTFI

To implement MDTFI, the faculty first enlisted the support of the Program Chair. The faculty met with the Program Chair, described the perceived issue (the failure of many design projects to meet all deliverable expectations) and the proposed intervention. The Program Chair immediately indicated her support for the intervention and this research project and encouraged the faculty to proceed with implementing the MDTFI.

Then, faculty modified the syllabi of the design course and the professionalism course and created the project management documents that were to be completed weekly. These weekly documents were intended to provide a constant low level of urgency. In other words, because the students were required to list their accomplishments each week they felt pressure to complete tasks. Furthermore, these assignments were designed to help students recognize where they were stuck or being ineffective with time management.

Students had no issues with the revised syllabi. In fact, after a few questions, the teams readily embraced the MDTFI except for the weekly documents. Initially some teams had difficulty embracing the weekly project management documents and making effective use of them. After a few weeks adjustment, however, teams started to make effective use of them.

Case Study Findings

The deliverable success rates of design teams as determined by faculty are reported in Table 1. A project was determined to be a failure if it did not meet the needs of the client in any substantial way and if no groundwork was established for future projects. If the project laid the groundwork for improvement, but still did not meet the needs of the client, the project was identified as mitigated failure (e.g. a project with core work worth building upon by a design team in the following semester). If a project largely met the needs of the client, but without all necessary features, precision, or capability, the project was labeled a mitigated success. Finally, if the project met all client needs, it was identified as an unmitigated success. The table reveals that in the semesters prior to Fall 2015, half of the projects were failures and no project was an unmitigated success. In 2015, only one of the five projects was a failure and one project was an unmitigated success.

Table 1. Success Rate of Design Projects

Semester	Teams	Failure	Mitigated failure	Mitigated success	Unmitigated success
Fall 2014	4	2	1	1	0
Spring 2015	4	2	0	2	0
Fall 2015	5	1	2	1	1

Faculty Reflections

Each design team benefitted from the MDTFI. Moreover, various aspects of the intervention affected learning and team outcomes. Allowing the evolution of requirements had advantages. For example, in one project, a client specified a series of gasses for the team to detect at various levels. The student team assigned to this project explored available sensors and found that the original specifications were unrealistic within the budget specified for a particular gas. Allowing the students to renegotiate the specifications meant that their energy and time was spent making sure they achieved core functionality rather than on having the individual components to meet the original specifications.

Part of the logic behind tracking weekly activities was to shed light on high-cost, low-impact tasks. For example, one team decided to emulate the conveyor line of a manufacturing facility. This was not directly part of their design project, but rather a step that would enable them to make measurements on campus reducing the time commitment of both the team and the project sponsor. Originally, the task was scheduled for one week; but in the end, it took three weeks. Had the team been more cognizant of cost and benefit of this task they could have chosen to spend their time more effectively. As it was, they were, at least, able to mitigate the damage by being aware of how much time had been spent.

Additionally, students were asked to consider risk as part of the way they chose which tasks to complete first. As was discussed earlier, by attacking the components of their project that were most likely to fail, mitigation could be done earlier rather than later. As an example of this, consider the project team that had to make distance measurements in fluid using a laser measurement system. This project had been carried over from the previous semester (i.e., Spring 2015) due to the earlier team failing to complete the tasks. In the past, students had focused primarily on the hydraulic systems for moving the fluid. The tools and techniques to design and fabricate such a system are well known and robust. In other words, with sufficient time, any competent team could have solved this part of problem. A more risky component of the problem was the laser-measuring system that was designed to measure objects in air, but needed to be understood and calibrated to measure objects in fluid. In Fall 2015, the team working on the project began by putting substantial resources into ensuring that this component worked in the necessary application and the team was more successful overall than they were the previous semester. An alternative explanation is that because this project was carried over from the previous semester the students had some familiarity with it and were able to use this knowledge to establish which components would be difficult earlier in the semester than they would have otherwise.

One team was tasked with designing a machine for a manufacturing process capable of increasing throughput. The manufacturing process involved shaping a proprietary plastic material with shape memory. They made particularly good use of risk mitigation by machining a prototype in the first few days of the semester. Using this prototype, they demonstrated that their proposed manufacturing process would add the features the client needed. The high-risk part of this project was that the client believed that heating would to be a necessary and the proposed process used mechanical force only. Using the prototype, the team demonstrated key functionality and achieved buy in from the faculty, the client, and themselves. This prototype was only designed to demonstrate minimum functionality. It had to be loaded and unloaded by hand, manually operated, could not handle the required raw material variations in the manufacturing environment, and produced inconsistent parts. The second prototype maintained the same basic process but was designed to accommodate the expected variability of raw material. It was only when the team designed the third prototype that they focused on achieving the required part specifications. With the capability to manufacture the specified parts the team developed three additional prototypes which sought to simplify the design. The first two of these three did not meet specifications but the third did. The result was that by the end of the semester the team had a simple and elegant fully functioning model that the client was excited to take to the next stage of development. It is worth noting that this team embraced the OODA loop and the use of failure to mitigate risk better than any other team. An alternative explanation for the

success of this team is that the project resonated well with the students and they would have been successful regardless of the process.

Conclusion

This case study revealed that the MDTFI improved the program's process of teaching engineering design. Each project team benefitted from the intervention. Various aspects of the intervention had stronger effects on some teams. The findings from this case study can be used to update and expand the MDTFI to include more effective implementation of project management by students. While the MDTFI improved the learning and performance of all teams, not all teams achieved a successful product outcome. Future work includes teasing apart the differences between successful design learning and successfully meeting client expectations. Additional work is needed to identify instructional strategies for engineering design that can help students achieve design success. Even though students are clearly learning technical outcomes, improving their design strategies and developing professionally, a fully successful project meeting industry, faculty and student expectations, provides a sense of accomplishment that can contribute to the development of engineering identity as well as set a stronger pattern for using design iterations and resiliency to failure.

The limitations of this study include that the intervention was conducted in one program over a limited time by two faculty members, who self-reported the case. The proposed explanation, that MDTFI positively affected student learning outcomes and success, should be further tested. Additional research can shed light on how changes in instruction for engineering design are affected by the characteristics of team members, the design projects that are chosen, the characteristics of the clients and the changes in the design processes.

The findings of this study have implications for the practice of instructing students on how to use engineering design models, and the importance that managing failure, iterative design, and risks have on student learning and outcomes. Given the importance of engineering design to the success of engineering students and project-based engineering programs, additional research on how to improve the instruction of engineering design is clearly warranted.

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