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Diffusion of Designerly Finite Element Analysis

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Diffusion of Designerly Finite Element Analysis

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Abstract

To address a variety of difficulties surrounding the use of finite element analysis (FEA) in product development at Sandia, this research explored a 'designerly' insertion of FEA into the design-build-test product development cycle. Designerly FEA is characterized by the use of simplified FEA models, designer-friendly FEA software, an FEA analyst embedded in the product design team, relative comparisons of design options, and a deliberate leveraging of routine prototype testing to collect model validation data. Two case study projects were used to explore the impact of this approach on the product development teams' thinking and perceptions of FEA. The case study data was collected using mixed methods and analyzed using a theory-building approach. The results were synthesized into a framework describing how the use of FEA to build confidence in a product design is related to the process by which product development teams gain or lose confidence in FEA itself. The implications may extend to other organizations that desire to increase the impact of simulation technologies in their product development process.

Acknowledgments

A tremendous number of people have provided support and encouragement over the course of this research, so it is my pleasure to acknowledge several of them here.

First, I would like to recognize Sandia's University Part-Time Program, not only for funding the majority of this investigation, but also for providing me the flexibility to pursue a topic that was of interest to both me and the Laboratories. The contents of this SAND Report also served as my Ph.D. dissertation at Stanford University.

I am indebted to my adviser at Stanford, Sheri Sheppard, who graciously accepted me as a non-traditional Ph.D. student. I thank her for her patient guidance and for sacrificing her time—and for consistently encouraging me to ask 'the big questions.'

I would like to thank my reading committee members, Kincho Law and Larry Leifer (both of Stanford), for offering valuable feedback on earlier drafts of this paper. I also thank my other committee members, Laura McNamara (Sandia) and Steve Barley (Stanford), for pointing me to literature from the fields of diffusion studies and ethnographic research.

I thank my fellow Sandians who made time to take the online FEA survey, and I especially thank those who participated in the case studies. I thank Rex Eastin and Kathryn Hughes for their enthusiastic support, and Terry Reser, who helped me navigate the hurdles of human studies research.

I thank my colleagues at Stanford, especially Samantha Brunhaver and Helen Chen, who helped refine the FEA survey and interview protocols, and who also conducted the interviews. I also owe a big thanks to Mark Schar, Bill Cockayne, and Tamara Carleton, whose ideas and feedback had a substantial impact on the 'naming and framing' of this research.

I offer overdue thanks to my professors from Oregon State University, Derald Herling and the late Richard Peterson (no relation), who years ago encouraged me to pursue a Ph.D.

I thank my parents, Tony and Wini, and my wife's parents, John and Pam, for their steadfast support. I also appreciate the encouragement offered by the rest of our family members and by our friends at Cornerstone Fellowship in Livermore, California.

Above all, I owe thanks to Bernadette, my wonderful wife and best friend, who has patiently walked side-by-side with me on this journey. She offered unwavering support and was always ready with encouraging words, never once taking the opportunity to make me feel guilty that I was ambitious enough (and perhaps foolish enough) to take all of this on.

Finally, and quite frankly, I owe thanks to God, who faithfully and amazingly orchestrated countless details so that I could somehow complete this larger-than-anticipated research project while working at Sandia and raising a family.

> Don't fret or worry. Instead of worrying, pray. Let petitions and praises shape your worries into prayers, letting God know your concerns. Before you know it, a sense of God's wholeness, everything coming together for good, will come and settle you down. It's wonderful what happens when Christ displaces worry at the center of your life.
>
> Philippians 4:6-7, The Message

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Executive summary

Increased utilization of finite element analysis (FEA) in the product design and development process—a goal widely recognized across various disciplines and industries—is, at its core, an issue of technology diffusion. An online survey distributed to a wide audience in the product development community at Sandia National Laboratories in Livermore, California revealed a variety of difficulties, past failures, and conflicting points of view regarding the use of FEA. The survey was distributed in January, 2012 and again in January, 2014, with the survey results (provided in Chapter 3) forming a baseline for this investigation. The survey distribution was similar to the distribution shown for this final report, and approximately 60 [anonymous] responses were received for both the 2012 and 2014 surveys.

To address several of the identified hurdles, this research explored a 'designerly' insertion of FEA into the design-build-test product development cycle. In contrast to more established approaches, designerly FEA (discussed in Chapter 4) is characterized by the use of simplified FEA models, designer-friendly FEA software, an FEA analyst embedded in the product design team, relative comparisons of design options, and a deliberate leveraging of routine prototype testing to collect data for validating the FEA models.

Designerly FEA was implemented in two case study projects (Chapters 6 and 7) by the research investigator, and the resulting impact on the product development teams' thinking and perceptions of FEA was investigated via participant-observation using a combination of survey and interview data collection methods (described in Chapter 5). The case study data was analyzed using a theory-building approach to generate a framework for describing how the use of FEA to build confidence in a product design is related to the process by which product development teams gain or lose confidence in FEA itself (Chapters 8 and 9). The resulting model describes how various factors identified in this investigation enhance (or erode) a team's outcome and efficacy expectations regarding the use of FEA, thereby increasing (or decreasing) their motivation to rely on it in their product development approach. A graphical overview of the research process is provided in Figure 1.

The remainder of this executive summary highlights the investigation's major findings, and provides corresponding recommendations to Sandia line and program management for promoting an enhanced yet balanced utilization of FEA in product development. The teams in the case studies were strongly representative of the Sandia product development community in terms of their technical backgrounds, present roles, lengths of time at Sandia, and previous exposure to FEA (Sections 6.1.2 and 7.1.2), so these findings should hold applicability across a broad portion of the Laboratories' development work. The implications may well extend to any organization that desires to increase the impact of FEA, computational fluid dynamics, electrical and electronics simulation, or multi-physics simulation in their product design and development process.

Target product development activities where FEA can enhance design confidence. This research revealed that above all else, product development teams view the purpose of FEA as improving confidence that their designs meet performance requirements. Conversely, they view FEA negatively when, for one reason or another, it fails to serve this purpose. Future diffusion or intervention efforts should specifically target applications where FEA is well-suited to unambiguously enhance confidence in product performance. This requires an informed view of both FEA technology itself and the potential product development applications where it might be most beneficial. Though FEA is impressive, advocates should take great care to avoid any hint of the view that it is somehow a good fit for all types of products and needs.

Demonstrate the applicability of FEA for evolutionary and/or experimentally-tested products. FEA is often only one of many potential sources of design knowledge. In such instances, FEA can only rightfully be used if it provides value in the presence of these other factors, which may hold a strong precedence in the minds of the responsible product design engineers. Future diffusion or intervention efforts should consciously demonstrate ways in which FEA can contribute to enhanced design confidence, even when prototype testing is required or strong similarity exists to previously-tested designs. Doing so may be very effective at introducing FEA to an untapped audience of design engineers, who will conceive of their own applications for intelligently leveraging FEA alongside experimental product testing and/or for relative questions aimed at making existing products better.

Emphasize tangible impacts to product design. This research revealed that of the various manners in which FEA can enhance design confidence, product development teams hold a particularly strong expectation that FEA should directly impact product design. As a result, they take note when the use of FEA does not result in demonstrable changes in the physical configuration of the product. Exemplars of FEA in product development should be selected that exhibit significant feedback from FEA into the product design itself, rather than only verifying that the product design was adequate, or only demonstrating that FEA can accurately predict experimental data (although each of these also important elements of a diffusion effort).

Involve FEA analysts in testing, and ensure the visibility of FEA validation activities. This research revealed that confidence in FEA must be earned, and that an effective and necessary step in achieving this is providing direct comparisons of FEA results and experimental test data, so that teams can judge the merits and adequacy of FEA for themselves. This seems like a fairly obvious point, but its effectiveness and importance cannot really be overstated. Team meetings are probably the most effective venue for this type of information sharing, but project reports, internal white papers, and/or seminars might reach an even wider audience. Consideration should be given to presenting validation metrics that, when possible, are familiar and intuitive to the product development team. This should ensure that the effectiveness of the FEA modeling capability is not misunderstood to be either better or worse than it actually is. To facilitate this, FEA analysts should be more directly involved with prototype testing during product development. However, this research suggested that demonstrating the accuracy of FEA results is only the first step toward securing a foothold in a design team's thinking, so this recommendation should not be given undue priority over the others listed here.

Explore co-location of FEA analysts and design teams, or FEA training for design engineers. This research revealed that confidence in FEA must be earned, and that an essential step in achieving this involves securing the product development team's confidence in the person performing the FEA. This demands stronger ties between the community of FEA analysts and experts and the product development community. To this end, Sandia should explore embedding FEA analysts more fully in design teams, and/or co-locating FEA analysts with project and design groups to enhance comradery. Another option would be to explore FEA classes and training for interested design and project engineers. In any case, Sandia should be diligent to prevent placing newer or less-experienced FEA analysts in project assignments without a reasonably clear path forward on how FEA can assist in the team's product development task. For example, very difficult or ambiguous projects should require the participation, or at least oversight, of an experienced FEA analyst who is familiar with product development needs and challenges.

Strive for strong alignment between FEA and product deliverables. This research revealed the importance placed by the product development community on achieving a true integration of FEA into the design and development process. It is the opinion of the research investigator that achieving an improved level of integration is largely dependent upon experts in FEA understanding the product development process and knowing how to use FEA in such a way that maximizes its benefits while minimizing the additional burden it places on the development team and its resources. To that end, Sandia should consider deliberate actions to ensure that the goals and deliverables for both project teams and their FEA experts are consistent. This consistency should span several aspects of Sandia's product development work, including project budgets and schedules, research and advanced development, research publications, interfacing with customers and stakeholders, requirements formation, conceptual design and design optimization, prototype assembly, test planning and execution, quality control, safety, security, project documentation, and manufacturing.

Expertly scope FEA to fit project timelines using a designerly approach. This research revealed that it is difficult to broadly overcome the perception, where it exists, that using FEA takes too long to be practical for real product development. Future diffusion or intervention efforts concerned with securing the confidence of product development teams should make every possible effort to demonstrate that the use of FEA can be expertly and reliably scoped to fit within the constraints of project schedules. All possible trade-offs in terms of modeling techniques, scope, fidelity, accuracy, and/or uncertainty should be considered and weighed alongside project-specific needs, which may (or may not) be able to make use of less-capable models in return for quicker model development and run time. This type of trade is especially important for classes of products with a strong conceptual-design element, short development times, and/or established prototype testing practices, as they may present a particularly strong opportunity to utilize designerly FEA.

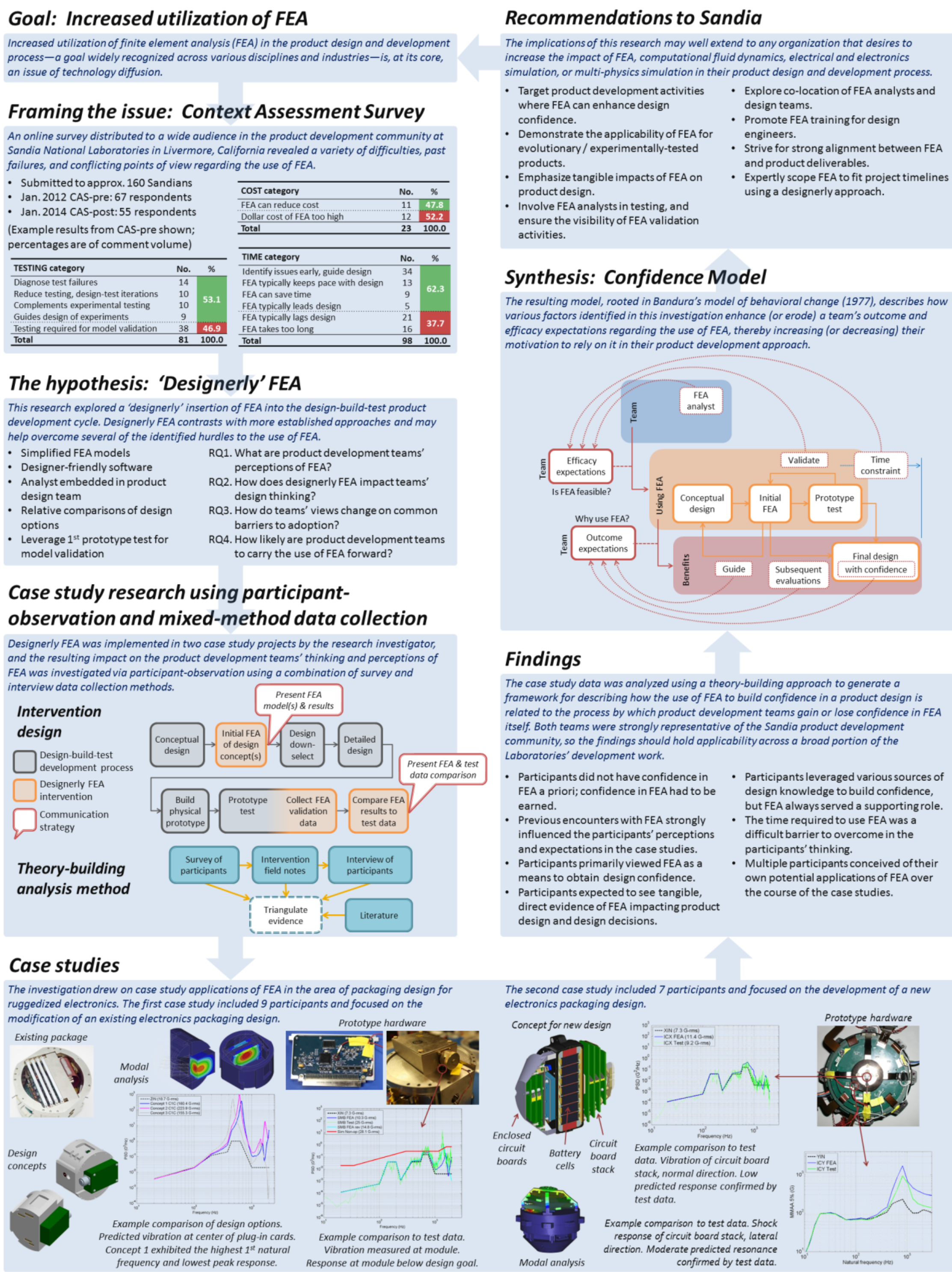


Figure 1: Graphical overview of the research process.

1 Introduction

> Few tools have shown such great power and promise for the future of product design as finite element analysis (FEA). The ability to simulate the performance of a part or system prior to building a physical prototype is only beginning to filter into the world of design engineering.
>
> Adams and Askenazi (1999, p. xxix)

Finite element analysis (FEA) is a powerful computational tool for simulating a variety of mechanical, thermal, and electromagnetic phenomena. It is widely recognized as providing substantial benefits to product design and development in a diverse range of industries including aerospace, automotive, and consumer products. But as this research reveals, FEA faces negative perceptions in the product development community. This dissertation is the culmination of a two-year investigation into issues underlying this resistance.

Section 1.1 provides a brief overview of FEA, and Section 1.2 describes the motivation for this research. Section 1.3 introduces the idea of *designerly FEA*, which recasts the vision of FEA to include more focus on its potential as a tool for engineering design, rather than an exclusive focus on its use as a tool for engineering science. Section 1.4 describes the four research questions that were formulated to guide this investigation, and Section 1.6 provides an outline of this dissertation.

1.1 Finite Element Analysis (FEA)

Finite element analysis (FEA) generally refers to engineering analysis involving application of the finite element method (FEM), a numerical technique for approximating solutions to large systems of partial differential equations. The method involves discretizing, or *meshing*, a complicated geometry into many smaller, simplified regions, called *elements*. The technique was originally developed in the 1950s and 1960s for solving problems in structural and solid mechanics in the aerospace industry, enabled by the development of analog mainframe computers (Adams, 2006, p.13; Géradin and Rixen, 1997, p. 2). By the 1980s, FEA had been generalized for use in other engineering fields, such as heat transfer and electromagnetism, and had become a more widespread analysis tool for engineering, largely enabled by the growth of personal computers and workstations (Adams and Askenazi, 1999, p. 5-7). Rigorous derivation of the numerical technique is covered extensively in previous literature, with foundational texts including Zienkiewicz (1971), Strang and Fix (1973), Szabó and Babuška (1991), and Hughes (2000).

Without FEA or other related numerical techniques, engineers are limited to the use of closed-form equations addressing the most common geometry and boundary conditions. As an example, an authoritative and comprehensive reference from the field of solid mechanics is Young and Budynas (2002). These closed-form solutions—though painstakingly derived from the governing partial differential equations—constitute a fairly limited set of constraint and loading conditions for a handful of very idealized geometries such as bars, beams, plates, spheres, and cylinders. The power of FEA lies in the fact that it permits the analysis of virtually *any* geometry under an extremely wide variety of constraint and loading conditions. This makes FEA an incredibly powerful tool for engineering analysis. For example, in mechanical product design, engineers routinely need to understand the behavior of parts or structures in response to various types of external loading, such as forces, pressures, and inertial loads—that is, how the parts deflect or deform and, ultimately, the loading levels at which they fail. Using FEA provides engineers a means to analyze a nearly limitless variety of part geometries and loading conditions.

1.2 Research Motivation

Engineering design and product development activities have traditionally been built around an iterative and largely empirical process that involves generating a conceptual design, building a physical prototype, and testing it to ensure it meets design requirements. The dramatic increase in analysis capability enabled by FEA is widely recognized to offer substantial benefits to this process, such as improved identification and correction of product failures, enhanced design performance and understanding, a reduced number of design-build-test iterations, and a corresponding reduction in development time and costs (Adams, 2006, p. 1). For these reasons, management often takes the lead in pushing for the use of FEA in product development (Adams and Askenazi, p. 349).

Sandia National Laboratories[1] is no exception to this, with upper management generally calling for the use of FEA in much of the research, design, and product development activities across the Laboratory. For example, a recent internal presentation by Sandia management emphasized the following 'success' criteria, among others, for computational simulation at Sandia (Dimos, 2012):

- increased use and impact of computational simulation throughout Sandia programs;
- critical engineering analysis delivered in a time frame consistent with design iterations;
- improved integration of computational and physical simulation;
- computational models used to support all test and evaluation programs; and
- increased use of computational modeling as a discovery tool for driving experiments.

To be clear, Sandia already possesses and uses simulation capabilities that are world-class in every regard. For example, Sandia maintains licenses for several of the most capable commercial FEA codes, such as Nastran, Ansys, Abaqus, and LS-DYNA. In order to address a variety of unique and challenging physical phenomena, Sandia has developed several of its own, 'in-house' simulation codes, a sampling of which is provided for reference in Table 1. Additionally (and impressively), Sandia has been deeply involved in the development of massively-parallel supercomputing capabilities, including the systems ASCI Red, Red Storm, and most recently Red Sky (Sandia Labs News Release, 2009). Each of these systems, at their time of deployment, has ranked in the top ten of the world's fastest supercomputers. To develop and leverage these computational capabilities, Sandia routinely recruits and retains talent with advanced degrees from the nation's top universities in the areas of science, engineering, and computer programming.

[1] Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. This research was funded under Sandia's University Part-Time Program.

**Table 1: Partial list of codes developed by Sandia National Laboratories.
More information on these computational simulation codes is provided in the References.**

Adagio	Aria	CEPTRE	DAKOTA	Krino	Presto	VIPAR
ALEGRA	Calore	CTH	Fuego	Premo	Salinas	Xyce

Any room for improvement at Sandia in the use of computational simulation, including FEA, does not appear to be for lack of technical prowess or credentials. On the contrary, the goals expressed by management allude to other directions for improvement, such as "increased use," "time frame consistent with design iterations," "integration of computational and physical simulation [i.e., experimental testing]," and "use… as a discovery tool". Past uses of FEA in product development have been notoriously difficult and have not met consistent success, as demonstrated by the results of a pilot study presented in Chapter 3. It is the contention of this research investigator that FEA will continue to have a limited impact in product development if FEA cannot effectively be drawn into the thinking and decision-making of multidisciplinary design teams. To this end, it is essential to develop a deeper understanding of how design team members from a variety of technical backgrounds perceive the benefits and limitations of FEA in the context of real projects.

1.3 'Designerly' FEA

An approach to using FEA that meets the most pressing needs of product design and development teams is warranted. As discussed further in Chapter 3, the desire exists for FEA to guide design decisions and assist in the early identification of design issues, while ensuring that FEA is both (1) performed quickly enough to support product development timelines, and (2) intelligently and synergistically coupled with experimental testing. The consistency of these themes with the guidance from Sandia management (Dimos, 2011, quoted in Section 1.2) is striking. All of this must be accomplished in a cost-effective manner.

In an effort to achieve these goals, this research utilized an approach to FEA that is somewhat unconventional at Sandia National Laboratories. It is simply termed *designerly FEA*. The intent is to pull the idea of FEA back from the domain of custom codes, supercomputers, and exceedingly complex phenomena that the typical product design engineer is not routinely confronted with. Far from a new idea, designerly FEA represents a 'back-to-the-basics' approach, built on trusted principles surrounding the use of FEA that are discussed in more detail in Chapters 2 and 3. The aim is to take advantage of enormous improvements in the usability of modern commercial FEA software combined with the horsepower of modern desktop computers to put FEA in the hands—and minds—of design engineers. Designerly FEA can be summarized as consisting of the following main points.

- Simplified FEA models are used to the extent possible to promote improved turn-around times.
- Designer-friendly FEA software is used to improve integration between design and FEA models and activities.
- The person performing the FEA modeling is fully embedded in the design team to promote effective communication between FEA and product development.
- When possible, FEA is used for relative comparisons of design options or decisions, rather than using FEA exclusively to predict absolute answers.
- Testing of the first physical prototype is used as an opportunity to gather experimental data for FEA model validation.

It is proposed that a designerly approach to using FEA will contribute to meeting many of the identified goals for FEA in the realm of product development.

1.4 Scope

This investigation drew on case study applications of FEA in the area of packaging design for ruggedized electronics. Packaging design is characterized by the need to 'fit' a selected array of components and/or functionality into a defined volume allotted for a product. Ensuring the ruggedness of electronics packaging designs is an important task in the automotive, aerospace, and consumer electronics industries. In these applications, environmental extremes such as temperature, vibration, shock, and humidity often necessitate particular design features and product testing to ensure that the electronics remain protected and functional over the lifetime of the product. Several uses of FEA in the area packaging design for ruggedized electronics are reviewed in Section 4.3. While this is a topic with broad applicability, it nonetheless represents a particular application of FEA and a distinct variety of design work. The resulting limitations of this research and the applicability of the findings to other classes of products and other applications of FEA are discussed in Sections 8.3 and 9.6.

1.5 Research Questions

The goal of this research was to investigate how the use of designerly FEA on real design projects might help overcome the negative perceptions of FEA that exist in the product development community. Chapter 5 describes the research methodology, which essentially relied on the researcher performing FEA in support of two case study product development efforts while investigating the resulting impact on the product development team members, who were participants in the case studies. The following research questions were developed to guide the investigation. Their formulation was influenced heavily by the previous literature reviewed in Chapter 2, but they are presented here as part of the introduction to the research.

RQ1. What are the product development teams' perceptions of FEA? The goal was to investigate the contentious, often contradictory perceptions of FEA identified in the pilot research, using the case study teams as a vehicle. The focus was on exploring their views of the benefits, adequacy, and inherent assumptions of the FEA models. The extent to which design teams have confidence in FEA emerged as a key topic and was also investigated.

RQ2. How does designerly FEA impact the teams' design thinking? The goal was to identify specific manners in which FEA affected their confidence in the product design, their understanding of the design's behavior, or their view of the roles of testing and FEA. At the center of these topics is the issue of how information gained from FEA intersects with other sources of design knowledge, as discussed in the works by Schön (1983) and Cross (2007).

RQ3. How do the teams' views change on common barriers to adoption? Rogers (2003) discusses extensively how different 'barriers' prevent an individual from placing confidence in an innovation, thereby halting their adoption of the innovation and thus limiting its diffusion through a population. The pilot research confirmed that several barriers to the adoption of FEA are active at Sandia, including the length of time required, the high dollar cost, the difficulty of integrating FEA with product development, and the inescapable need for validation testing. The goal was to understand the extent to which these common barriers could be overcome, which would be useful information to Sandia to support diffusion of FEA into more of the company's product development lines.

RQ4. How likely are the product development teams to carry the use of FEA forward? Evidence that the design team members grow in their desire to understand FEA, conceive of new applications for it, and develop their own opinions on how it should (or should not) be used were all investigated. The goal was to determine how likely the team members were to carry the use of FEA forward to future projects.

The findings from the individual case studies presented in Chapters 6 and 7 led to the formation of the Confidence Model shown in Figure 2. It describes how the use of FEA to build confidence in a product design intersects with the process by which the product development team gains or loses confidence in FEA itself.

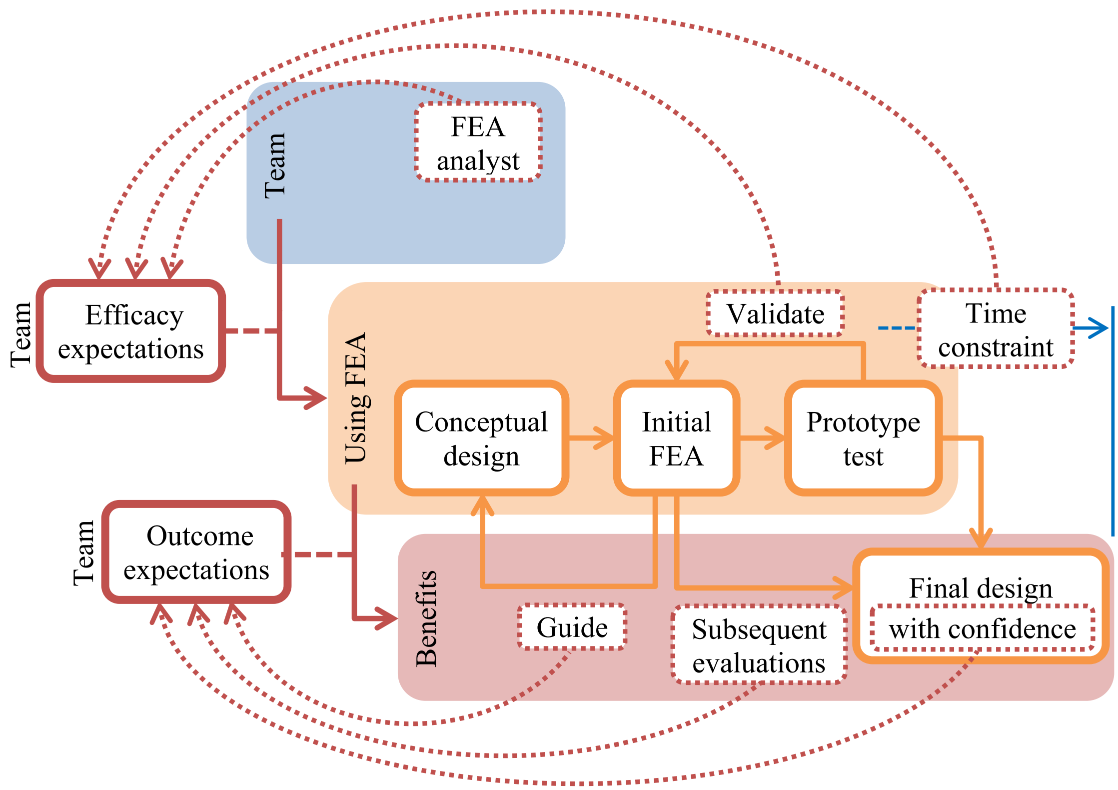


Figure 2: Confidence Model.
The Confidence Model describes how the use of FEA to build confidence in a product design intersects with the process by which the product development team gains or loses confidence in FEA itself. The model is rooted in the findings of this investigation and is discussed in Chapter 9.

1.6 Outline

Following the introduction and general background provided here, this dissertation is divided into eight more chapters. Chapter 2 reviews the extant literature from various fields that was influential in shaping this research. Chapter 3 discusses the context for this research at Sandia National Laboratories, presenting an assessment based largely on the results of an online survey conducted at the beginning and end of the two-year investigation period. Chapter 4 further discusses the idea of designerly FEA, which is proposed as a means to increase FEA's impact in product development and was utilized in this research as an experimental intervention in two case study projects. Chapter 5 describes the case study research methodology, which was reflective in nature and relied on participant-observation and mixed-method data collection to assess the impact of designerly FEA on the product development team. Chapters 6 and 7 present detailed reports on the two individual case studies, with the intent to offer a holistic view of the product design task, the use of designerly FEA for predictive analyses and in conjunction with physical prototype testing, and the resulting impact on the thinking of the product development teams. Chapter 8 compares and contrasts the two case study projects and the findings from each. Chapter 9 presents a final discussion of the findings from this investigation, which are synthesized in the Confidence Model introduced above.

2 Literature Review

> Every scientific field makes certain simplifying assumptions about the complex reality that it studies. Such assumptions are built into the intellectual paradigm that guides a scientific field. Often these assumptions are not recognized, even though they affect such important matters as what is studied and what ignored… So when a scientist follows a theoretical paradigm, a set of intellectual blinders prevents him or her from seeing certain aspects of reality. "The prejudice of [research] training is always a certain 'trained incapacity': The more we know about how to do something, the harder it is to learn how to do it differently" (Kaplan, 1964, p. 31).
>
> (Rogers, 2003, p. 106)

The development of finite element analysis since the 1960s has occurred rather coincidentally with the rise of the field of design research, which has roots in the same decade. This chapter reviews literature from these fields and others that have been influential in shaping this investigation. Section 2.1 reviews works aimed at defining and describing what 'design' is, particularly in contrast with science. Section 2.2 reviews several models of the design process presented in the literature. Section 2.3 covers a variety of publications that have presented examples of, or sought to generalize, the use of FEA in the design process. Section 2.4 introduces diffusion research, describing the attributes of innovations as well as a model for how decisions are made to adopt (or reject) them.

2.1 The Nature of Design

Since the 1960s, the nature of 'design' as distinct from that of 'science' has been actively debated in academic and educational circles. In essence, this debate is rooted in a backlash against a larger movement that aimed to enfold engineering design activities into a scientific framework.

Schön (1983, p. 21-69) offered a synopsis of thinking about the professions in general, and engineering in particular, that led to this countermovement. He traced the rise of Positivist thinking and its ultimate influence in the form of the models of 'technical rationality' and 'applied science'. In these schools of thought, basic science is the foundation of a profession and its application yields applied science; applied science generates diagnostic and problem-solving techniques which are in turn used in practice in the delivery of actual products and services (1983, p. 24-25). After World War II this view had become firmly established, but by the late 1960s some practitioners and educators were questioning the move to portray engineering exclusively in the framework of "engineering science" (1983, p. 171). A prominent dean of the Harvard engineering program was among the first to point out the drawbacks, citing the need "to bridge the gap between a rapidly changing body of knowledge and the rapidly changing expectations of society," which required "an art of engineering" (1983, p. 171). But enormous public support for science in the 1950s and 1960s led engineering schools to follow the vision of engineering science, focusing rather exclusively on "the possibility of the new" rather than "the design capability of making something useful" (1983, p. 171). The art of engineering was effectively subordinated to the science of engineering.

In a related line of thinking, and at around the same time as Schön's publication, Archer (1979) and Cross (2007, p. 17-18; first published in 1982) distinguished design from both the sciences and the humanities, summarizing its nature as follows.

- Design is concerned with 'the conception and realization of new things' and is the collected body of experience, skill and understanding embodied in 'the arts of planning, inventing, making and doing.'
- At the core of design is the language of modeling.
- Design has its own distinct things to know, ways of knowing them, and ways of finding out about them.

Cross further contrasted design and "technology" with the sciences and humanities, as summarized in Table 2, articulating a third and distinct realm of human knowledge. He described several characteristics of design (2007, p. 51-54), several of which are summarized below, that provide a convenient framework for further expounding the often subtle yet important ways in which design differs from purely scientific activities.

Table 2: Contrasting design with the sciences and the humanities. Adapted from Cross (2007, p. 18).

Field	Focus of study	Appropriate Methods	Values
Sciences	Natural world	Controlled experiment, classification, analysis	Objectivity, rationality, neutrality, truth
Humanities	Human experience	Analogy, metaphor, evaluation	Subjectivity, imagination, commitment, justice
Design (or Technology)	Artificial world	Modeling, pattern-formation, synthesis	Practicality, ingenuity, empathy, appropriateness

Design is exploratory (Cross, 2007, p. 52). Design possesses an element of discovery. "The creative designer interprets the design brief not as a specification for a solution, but as a kind of partial map of unknown territory… and the designer sets off to explore, to discover something new" (Cross, 2007, p. 52). The ensuing design activity is difficult to chart ahead of time.

> All the relevant information cannot be predicted and established in advance of the design activity. The directions that are taken during the exploration of the design territory are influenced by what is learned along the way, and by the partial glimpses of what might lie ahead.
>
> (Cross, 2007, p. 52-53).

Design problems are ill-defined (Archer, 1979; Cross, 2007, p. 52). Design problems tend by their very nature to be ill-defined, which Asimow (1962) noted decades ago.

> Problems seldom come ready-made with a fine, clear statement of the factors involved and a sprinkling of well-marked clues to indicate the one correct solution. Indeed, it is usually unclear whether there is a single problem or several, and, if there are several, what they are. The designer is presented, not with a problem, but with a problem situation, a situation which may have many perplexing elements interrelated in complicated and obscure patterns. It is out of this milieu of perplexity that clear definitions of the relevant problems must be drawn.
>
> Asimow (1962, p. 44)

Design practice therefore involves problem *setting* as much as it involves problem *solving*—or, in Schön's other words, the activities of *naming* and *framing* (1983, p. 40). "Designers select features of the problem space to which they want to attend (naming) and identify areas of the solution space in which they choose to explore (framing)" (Cross, 2007, p. 102). As a result, the design process involves iteratively changing or reframing the problem as needed (Schön, 1983, p. 78-79), with a difficult type of feedback between the solution and the problem. "In design, the solution and the problem develop together" (Cross, 2007, p. 52) because "'the information needed to understand the problem depends upon one's idea for solving it'" (Dubberly, 2004, quoting Rittel and Webber, 1973). Among many issues, this fundamental disparity is perhaps the most important for understanding the difficulty of using FEA in design: FEA requires, by definition, a well-defined question, whereas design problems typically evolve with their solution.

Design is solution-focused and abductive (Cross, 2007, p. 37, 53, 101-102). Design involves a solution-focused strategy and relies on a unique type of logic. Cross (2007, p.23) quoted Lawson (1980) who observed that designers "… learn about the nature of the problem largely as a result of trying out solutions, whereas… scientists set out specifically to study the problem." Cross (2007, p. 23) summarized this, noting that "… scientists problem-solve by analysis, whereas designers problem-solve by synthesis". This solution-focused strategy enables further exploration and clarification of salient aspects of the design task. At its heart, this process is different than science, which relies on deductive and, more importantly, inductive reasoning. Deductive reasoning identifies 'what must be true'; given the truth of the assumptions, a valid deduction guarantees the truth of the conclusion. Inductive reasoning identifies 'what must be operative', i.e., a principle that can be shown to explain a pattern of observations via repeated experiment. Design, by contrast, involves so-called 'abductive' reasoning, a third type that proposes 'what might be' (Cross, 2007, p. 37). An abduction cannot be shown to be either 'correct' or 'incorrect' per se; rather, it serves as a reference point from which exploration of the proposed solution—as well as further exploration of the problem—can begin. Abduction has been described as "the logic of conjecture" (Cross, 2007, p. 37) and the kernel of creative design (Cross, 2007, p. 53).

> When all has been said and done about defining design problems and analyzing design data, there still remains the real crux of the act of designing—the creative leap from pondering the question to finding a solution. … If the solution to a problem arises automatically and inevitably

> from the interaction of the data, then the problem is not, by definition, a design problem.
>
> Bruce Archer (quoted by Dubberly, 2004)

Design is reflective (Cross, 2007, p. 53). Design relies on the use of a medium—traditionally, sketches and prototypes—to understand and refine the proposed design solution. “The sketch… enables half-formed ideas to be expressed and to be reflected upon: to be considered, revised, developed, rejected and returned to” (Cross, 2007, p. 53). More recently, 3D CAD software has become an integral part of this reflective process across many design professions.

Design is ambiguous (Cross, 2007, p. 54). Designers must be adept and comfortable at dealing with the inherent uncertainty that accompanies generating early, tentative solutions, which are “… necessary, but imprecise and often inconclusive” (Cross, 2007, p. 54). Schön, in discussing the importance of problem-setting, described professional practice as involving situations of “complexity, uncertainty, instability, uniqueness, and value-conflict”, noting that the model of ‘technical rationality’ is not well-suited to address such difficulties (1983, p. 39). In a related line of thought, he described a practitioner’s role with a situation as subjective: “… he must hold himself open to the situation’s back-talk. He must be willing to enter into new confusions and uncertainties… He must act in accordance with the view he has adopted, but he must realize that he can always break it open later…” (1983, p. 164).

Design is persuasive (Cross, 2007, p. 51). Finally, design—unlike science—has a persuasive element to it that does not present any sort of threat to required objectivity (Cross, 2007, p. 51). Cross quotes Lasdun (1965) as commenting that in design, the job is “’… to give the client… not what he wants, but what he never dreamed he wanted; and when he gets it, he recognizes it as something he wanted all the time.’”

2.2 Design Process Models

Despite this complex nature of design problems and design activities, both Cross (2000, p. 29-34) and Schön (1983, p. 128-140, p. 172) offered descriptions of design as a *process*, or as having a *structure*, that can be described. Dubberly generated a popular compendium of design process models from the fields of architecture, industrial design, mechanical engineering, quality management, and software development (2004). In it, he credited John Christopher Jones with describing, in 1962, the core of the design process as consisting of three steps: *analysis*, *synthesis*, and *evaluation*. Asimow (1962, p. 43-46) described the design process making use of these same three terms—and in doing so, referred to consensus in previous literature that the more general process of problem solving contained these three elements. Suffice to say that, whatever its origins, this three-stage descriptive framework appears to be heavily influential in subsequent design process models. Lawson (1990) described these same three steps of analysis, synthesis, and evaluation, and they are also evident in several of the models discussed below.

Asimow described 'analysis' as the step in which the design problem is drawn out and clarified (1962, p. 44). Next, he described 'synthesis' as the step in which one or more concepts are generated as a solution to the design problem (1962, p. 45-46). Finally, he described 'evaluation' as the analytical activity of assessing a design concept "in the abstract" against its performance requirements (1962, p. 46). Asimov's early description of the design process is depicted in Figure 3.

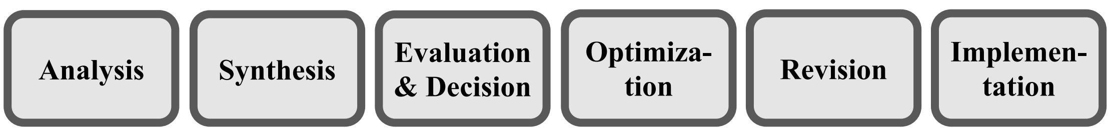


Figure 3: Early model of the design process, based on Asimow (1962, p. 43-47).
Asimow included six steps in his description of the design process, noting that "It is distinctively a process for solving the problems of engineering design, just as the scientific method is a process for solving the problems of research" (1962, p. 43). The model included the core 'analysis-synthesis-evaluation' steps.

The literature gives much attention to the relationship between analysis and synthesis activities. In contrast to a scientific approach, Dubberly quoted Lawson (1990) as noting that, "For the designers it seems, analysis, or understanding the problem is much more integrated with synthesis, or generating a solution." He further quotes Rittel and Webber (1973) who noted that "The information needed to *understand* the problem depends upon one's idea for *solving* it." Cross (2007) and Schön (1983) offered similar descriptions of this 'emergent' nature of design (Section 2.1), and Dubberly presented a simple model that nicely accounts for the overlap of these activities, shown in Figure 4.

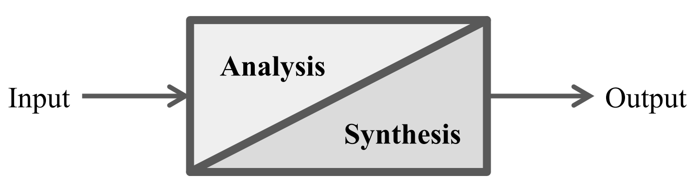


Figure 4: Relationship between analysis and synthesis, from Dubberly (2004).
The model accounted for the simultaneous activities of problem analysis and solution synthesis in the design process, while reflecting the gradual shift of focus from analysis to synthesis.

As with the analysis-synthesis overlap, many of the design process models presented in the literature address the relationship between the synthesis and evaluation steps, although generally without distinguishing between analytical and experimental forms of evaluation. Asimow omitted experimental testing in his description of the design process; he only mentioned tests in the context of discussing the 'revision' step (i.e., that test results often drive the need for design revision; p. 46). Ulrich and Eppinger (1995) published a model of the product development process that included 'testing of product concepts' as a distinct step. Their model also showed the 'building and testing of models and prototypes' as an ongoing activity throughout the process, but without any specific connectivity to the other steps in the process. Cross (2000, p. 30) proposed a four-stage design process, shown in Figure 5, depicting a feedback from the evaluation step to the 'generation' (i.e., synthesis) step. It is unclear from his descriptions, but Cross may have been focused on evaluation through analytical, non-experimental means, since he described "the end-point of the process" as "the communication of a design, ready for manufacture."

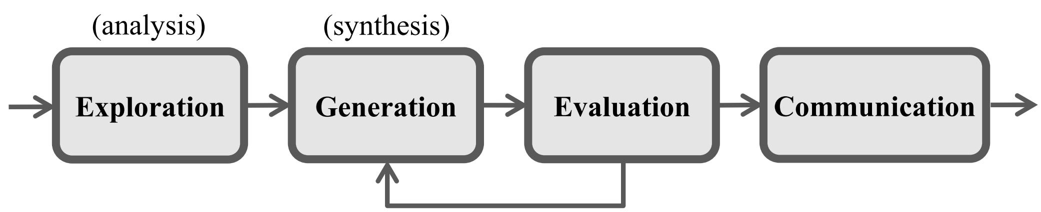


Figure 5: Design process model, from Cross (2000, p. 30).
Cross used the terms 'exploration-generation-evaluation' to describe the same core 'analysis-synthesis-evaluation' activities, and included a feedback from evaluation to generation.

Ullman presented a much more detailed model focused specifically on mechanical design that separately accounted for two distinct types of evaluation—the first focused concept down-selection, and the second focused on evaluating the selected concept for performance, manufacture, assembly, and cost (1997, p. 61). A simplified version of this model is shown in Figure 6. For the second stage of evaluation, Ullman discussed the need to select the most appropriate evaluation method, whether it involves analytical modeling, physical modeling (i.e., experimental testing), or both (p. 214-234). The difficulty of formularizing this fundamental decision might explain why most design process models do not distinguish between analytical and experimental evaluations.

Many design problems are in fact not one-dimensional, but hierarchical, i.e., the solution to a higher level design problem involves a decomposition into various sub-problems. Many published design process models attend to this complexity. Examples include the 'symmetrical problem/solution model' presented by Cross (2000, p. 59) and the 'Vee' model described by the International Council on Systems Engineering (2011, p. 27-31). A strength of the Vee model is its emphasis on the need to consider and plan evaluation activities in conjunction with the analysis and synthesis activities. Dubberly (2004) cites analogous Vee models from the software development industry. In general, none of these models attempt to distinguish between analytical and experimental means of evaluation.

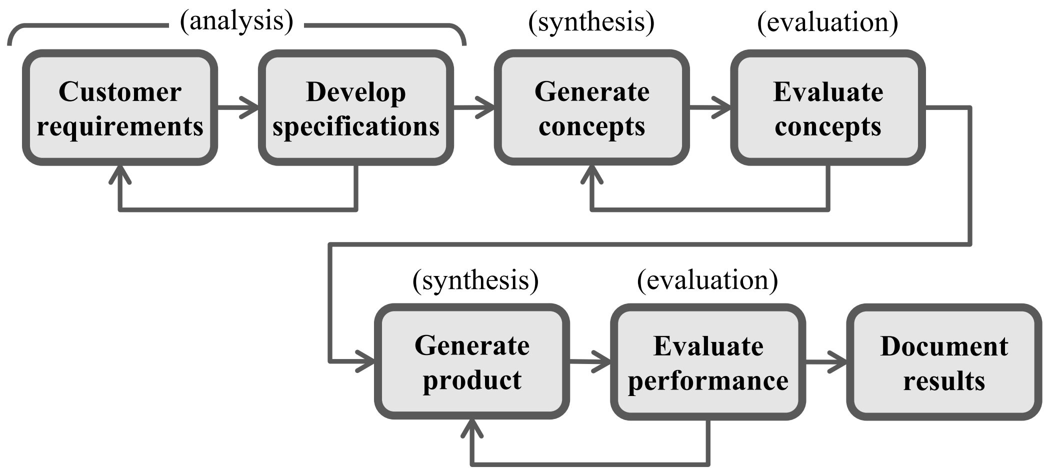


Figure 6: Elements of the mechanical design process, from Ullman (1997, p. 61).
This figure reproduces only the most essential elements of Ullman's much more detailed model. He included two types of evaluation—the first for selecting the best of several alternate concepts, and the second for evaluating the selected concept for performance, assembly, manufacture, and cost.

An exception to this is a model of the product development process utilizing "predictive engineering" presented by Adams and Askenazi (1999, p. 14), which is shown for reference in Figure 7. The core of this process consists of an iterative cycle using FEA or other simulation tools to evaluate design concepts and redesign as needed. They contrasted this approach with a more traditional product development process that relies on an iterative design-build-test cycle (i.e., using experimental evaluation only). Dubberly (2004) summarized an undated model by Alice Agogino (University of California, Berkeley) that was built around design-build-test, but also included the use of modeling early in the design process.[2] Agogino's model depicted a feed-forward from early modeling activities to fabrication of prototypes, but did not depict an feedback from prototype testing to the modeling activities.

[2] According to Dubberly (2004), Agogino's models were developed for NASA's Jet Propulsion Laboratory at the California Institute of Technology.

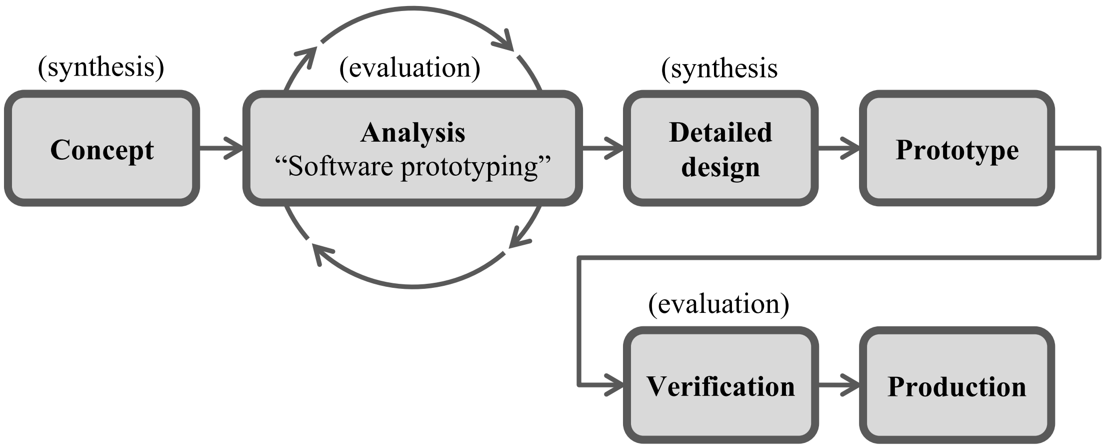


Figure 7: Product development process, from Adams and Askenazi (1999, p. 14).
Adams and Askenazi’s model included are rare delineation between analytical means of evaluation (i.e., “software prototyping”) and experimental means (i.e., “verification”). The model illustrated the temporal relationship between the two types of evaluation, but no other connectivity was depicted.

2.3 FEA in Design

The potential for FEA to impact the design process is widely recognized, and the quest to optimize and showcase its use in design is decades old. A variety of approaches to achieving this same fundamental goal are present in literature from the past 30 years. This section reviews several examples, including early research on FEA in conceptual design, published examples of FEA in design, custom FEA tools for using FEA in design, the use of simplified FEA models, and descriptions of the design process including FEA. A brief discussion of organizational barriers to using FEA in design is also presented.

Early papers on FEA in conceptual design. For at least three decades, researchers have focused increasing the relevance of FEA in design. For example, Clarke (1987 and 1988) examined the feasibility of using FEA during the conceptual design stage. He noted that at the time, the state of the art consisted of using FEA after the conceptual design stage, in parallel with detail design. Shinke et al. (1986) did pioneering work developing a custom design and analysis tool for use by structural engineers. Shephard and Yerry (1986) explored methods for automatically generating finite element meshes from CAD solid modeling geometry. Rudd (1988) continued the investigation of automatic mesh generation tools, similarly describing the potential for FEA in design.

> Finite element analysis (FEA) is commonly used to obtain information about structural behaviour without building prototypes. … Historically, FEA has been used primarily as an after-the-fact verification tool. … Using finite element analysis in earlier stages of design can better impact the actual design concept.
>
> Rudd (1988)

Rudd went on to conclude that

> … significant analysis productivity improvements can be made by using a solid modelling system that provides quick construction and manipulation of geometry, in combination with a free mesh generator that requires little user intervention to obtain acceptable meshes.
>
> Rudd (1988)

Wilson (1993) reviewed the historical development of FEM, noting how much remained to obtain true "automation" of the method. Among other conclusions, Wilson noted that (1) FEA programs must be fast to enable a full exploration of the design space; and (2) the need to automate the finite element method has been motivated by the solution of real engineering problems.

Examples of FEA in design. The literature is full of examples of the use of FEA in a wide variety of engineering design problems. Jha and Hornik (1995) detailed a process for optimizing the design of a plain milling cutter using FEA to model the stresses in the cutter teeth. Bamberg (2000) developed a methodical approach to the conceptual design of machine base structure that incorporated the early use of FEA to assess structural stiffness. Elm and Robert (2003) reported on a case study investigation of a small manufacturing company developing an in-house FEA capability, which permitted an integration of FEA into earlier stages of the design process and a resulted in improved productivity and superior designs. Kindt et al. (2003) presented the use of FEA in the design of an atomic force microscope, to assess and substantially enhance the stiffness of its various elements, thereby improving noise immunity. Kurki (2010) examined the use of FEA in the structural design of a ship, specifically investigating the feasibility and benefits of generating the finite element mesh directly from the CAD geometry. Park et al. (2010) used FEA for both static and dynamic analyses to optimize the resonant frequency of a compact vertical scanner for an atomic force microscope. Renhua et al. (2011) presented the use of FEA, along with other numerical simulation tools, to model the performance of an engine valve-train design.

Analysis tools for improving integration of FEA and conceptual design. Another research thrust has been to develop tools that more fully integrate FEA into the design software and intuitive processes of designers. For example, in order to make analysis more interactive and relevant during conceptual design, Trevelyan and Wang (2001a,b) developed a method for modifying two-dimensional concept geometry and automatically achieving updated stress analysis results, built around a numerical method related to FEA known as the boundary element method. Terdalkar and Rencis (2006) later demonstrated a graphically-driven FEA technique for the commercial code ANSYS that can be used by an engineer to modify the geometry of a two-dimensional part and instantaneously view the resulting changes in predicted stress levels. This provides "an optimization process that is engineer-driven as opposed to mathematically-driven," which represents an intriguing possibility for truly enfolding the use of FEA into design. Kagan and Fischer (2000), Cirak et al. (2002), Hughes et al. (2005), Cottrell et al. (2006), and Schmidt et al. (2010) demonstrated various advanced mathematical formulations for FEA, each aimed at enabling a complete integration of the solid modeling information used by CAD and FEA, but it is unclear whether or how soon any of these are likely to be implemented in commercial software.

Knowledge-based engineering tools. Some research has focused on intelligently cataloging the work of expert FEA analysts in order to extend its use to design engineers. Binde (2002) described a system that utilized case-based reasoning to develop a knowledge database. The intent was to assist in the development of new FEA models by leveraging an automatically-generated database of previously-applied FEA modeling techniques. Sandberg et al. (2004) similarly describe the use of a knowledge-enabled engineering approach to the use of FEA in the design process for automobile bodies. Interestingly, they refer to the use of FEA "as an integral part in the design process to provide a deeper understanding concerning the performance of design" and to support "the iterative procedure of *synthesis-analysis* loops" (emphasis added). The tool they present is intended to permit designers with less analysis experience to perform preliminary design analysis in crash scenarios in a matter of hours, rather than waiting four to six weeks for a more detailed simulation of the complete automobile body to be performed by senior analysts. The preliminary simulations are not intended to replace the later, more formal analyses, but rather are intended to provide the design engineer an opportunity "to check his design against broken down requirements, as well as for fast relative comparison between different solution concepts."

Simplified FEA 'concept models' in the automotive industry. The automotive industry has historically been a leader in maximizing the impact of FEA in the design process, and is now leading the recent trend toward a 'back-to-the-basics' use of simplified FEA models by design engineers. For example, Schelkle and Elsenhans (2001) examined the use of simulation in the development of new car concepts, and distinguished between the needs during the early and later phases.

> In the concept-finding phase, the emphasis is on the rapid evaluation of the various vehicle concepts. … CAE [computer-aided engineering] mainly serves to calculate the overall structural behaviour of the car. … For CAE to be able to 'push on' the design in its early phases, the vehicle models must be generated before CAD data are made available and they must also be quickly modifiable.
>
> Schelkle and Elsenhans (2001)

Högberg (2001) presented the use of FEA to support the conceptual design of a secondary deck for a semi-truck trailer, employing relatively simple models consisting of beam elements. He observed that "… the approach of keeping the design problem simple is more reliable, controllable and effective than to perform complicated, long-lasting FE analyses." Toupin (2008a,b) discussed the trend in automotive and aerospace companies of having design engineers perform much of their own analysis using commercial FEA software, relying to the extent possible on tools that facilitate an automation of steps such as mesh generation and results visualization. Most recently, Donders et al. (2009) described a method for using FEA in the early design stages of an automobile development cycle, and Osborne and Prater (2010) discussed the use of FEA in the design of pickup truck boxes. These authors each made compelling arguments for the use of simplified FEA "concept models" early in the design process, noting that simple models were the first FEA models used in industry, but were later replaced as computational abilities increased. Osborne and Prater observed that the use of simplified FEA models "… is beginning to re-emerge as designers recognize the value an attribute-based model can add to conceptual design activities." Both Donders et al. and Osborne and Prater cited several specific reasons for this move: (1) detailed design models do not typically exist in the earliest stages of the product development cycle; (2) extremely detailed FE models are not necessary to support fundamental decisions about the design architecture and global behavior; and (3) inclusion of such additional detail in the FE models only serves to slow down the analyses. Finally, Donders et al. described a need for a tight coupling between conceptual design and rapid analysis that must occur in competitive markets where minimizing cost and time to market and maximizing product performance is essential.

Descriptions of FEA-centric design processes. Some recent literature has explored the perhaps obvious but easily overlooked question of what the design process would look like given an intelligent leveraging of existing FEA technology. For example, Taylor and Weisshaar (2006) investigated a "systematic, evolutionary structural design process" for the development of large wing structures in the aerospace industry. Their process consisted of a series of iterations between FEA and design activities, with each step in the process informing the next. The intent of the process was ensure that the information obtained from FEA was actually used to make design decisions. Adams (2006) described a "design-validate-commit" approach (p. 10-11) to the product development process.

> In this minor, yet important, adjustment to the traditional way of working, decisions are validated as they are conceived so that mistakes are caught as soon as possible in the process. This is essentially a cultural shift that may involve changes to the way CAD models are created, test data is accumulated, and analysis tasks are completed.
>
> Adams (2006, p. 10)

He contrasted this with the typical "design-commit-validate" approach (p. 6-7), in which a rush toward overly-detailed design—enabled by modern 3D CAD software—results in a psychological and/or emotional commitment to the design that is difficult to overcome, because in the designer's mind the design has achieved a level of viability. Most recently, Greiss (2011) investigated the use of FEA in the design process at Stanford University's Dynamic Design Laboratory, where a heavy reliance existed on a design-build-test development process, and instead proposed an economic method "to optimize the switching between simulation and rapid physical prototyping… to reduce total product development cost and time." Greiss also noted that "current literature does not completely explore the effects of finite-element analysis on the design process, designers or on engineers." The second research question, *How does designerly FEA impact the teams' design thinking?*, was formed in the spirit of this observation. The teams involved in this research are discussed in more detail in Chapter 5.

Organizational barriers to using FEA in design. The literature reviewed thus far has focused on design, the design process, and examples of various tactics that have been used to bring FEA into design. Several underlying dichotomies emerge from the discussion, including tasks (design and analysis), tools (capabilities of modern CAD and FEA software), and roles (design engineers and full-time analysts). Barley (1990) reviewed various perspectives on the complementary influences of both micro- and macro-social forces within organizations, and the alignment of technology and organizational structure that result from these forces. In Barley's framework, these tasks, tools, and roles might be well-described as micro-social factors, with fast, designer-friendly FEA software representing a new technology that drives an upward push, altering tasks and skills and creating, in turn, "… opportunities and pressure for modifying organizational structure" (Barley, 1990). Separately, Barley mentions the possible presence of downward, macro-social forces, in which "… entrenched interests, established ideologies, and institutional arrangements constrain the design, selection, and implementation of new technologies" (1990). Rogers also noted that barriers and resistance to change exist in organizations (2003, p. 149, 404-405).

2.4 The Innovation-Decision Process

Although FEA is not new, it can nonetheless be viewed as an innovation with respect to the iterative design-build-test process that has been used for centuries in engineering design. Rogers (2003) synthesized decades of research aimed at understanding how innovative ideas and practices are diffused through populations. He noted that the decision to accept or reject an innovation is not an instantaneous act, but rather a process that "consists of a series of choices and actions over time through which an individual or a system evaluates a new idea and decides whether or not to incorporate the innovation into ongoing practice" (2003, p. 168). He presented a model, shown in Figure 8, of this 'innovation-decision process', which consists of five stages in which the adopter passes from gaining initial knowledge of an innovation, to forming an attitude toward it, to making a decision to adopt (or reject), to implementing the new idea, and finally to confirming their decision.

In contrasting the persuasion stage with the knowledge stage, Rogers observed, "Whereas the mental activity at the knowledge stage was mainly cognitive (or knowing), the main type of thinking at the persuasion stage is affective (or feeling)" (2003, p. 175). He discussed the importance of the perceived attributes of an innovation, with a focus on potential adopters. He divided these attributes into five categories, which are described in Table 3. The emphasis that Rogers placed on perceptions supports this investigation's first guiding research question, *What are the product development teams' perceptions of FEA?* Additionally, it helped shape the third (and related) research question, *How do the teams' views change on common barriers to adoption?*

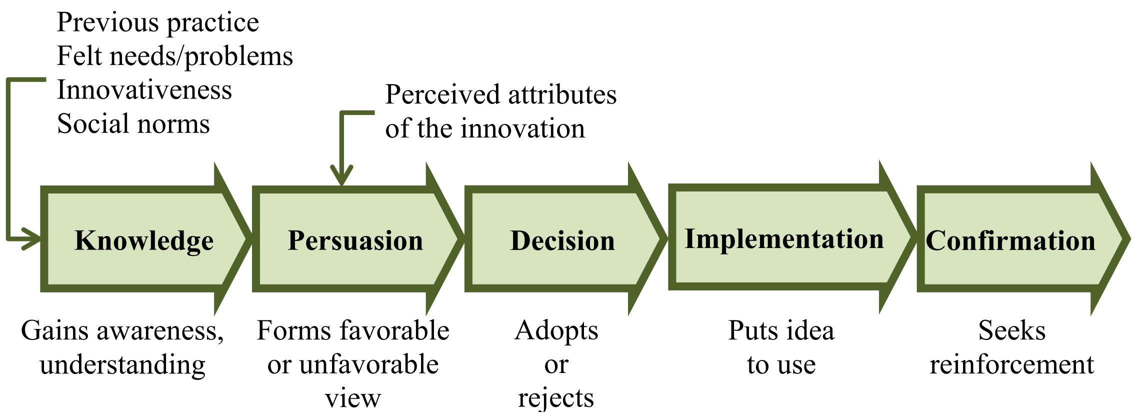


Figure 8: Innovation decision-process, from Rogers (2003, p. 170).
Rogers described the innovation-decision process as consisting of five stages. The perceived attributes of an innovation play heavily into the persuasion stage, when a favorable or unfavorable view of the innovation is formed by the individual or other decision-making unit.

Table 3: Rogers' perceived attributes of an innovation (2003, p. 229-258).
Rogers emphasized the importance that these perceived attributes have in determining an innovation's rate of adoption.

Perceived attributes of an innovation	Description
Relative advantage	*Is it better than the idea it supersedes?*
Compatibility	*Is it consistent with existing values, past experiences, and needs of potential adopters?*
Complexity	*Is it difficult to understand and use?*
Trialability	*Can it be experimented with on a limited basis?*
Observability	*Are the results easily observed by, and communicated to, others?*

In Rogers' model of the innovation-decision process, the final stage is the 'confirmation' stage, in which the adopter (or potential adopter) "seeks reinforcement for the innovation-decision already made, and may reverse this decision if exposed to conflicting messages about the innovation" (2003, p. 189). This accounts for a variety of scenarios that can occur. One who has adopted an innovation can either persist in its use or can discontinue its use; similarly, one who has rejected an innovation can either persist in that decision or can change course and adopt. The point is that for long-term sustainability, any initial commitment that a product development organization makes to using FEA will inevitably need to withstand the test of time and the difficulties associated with its use. This idea was the genesis of the fourth guiding research question, *How likely are the product development teams to carry the use of FEA forward?*

3 Sandia Context Assessment

> Perceptions count. The individuals' perceptions of the attributes of an innovation, not the attributes as classified objectively by experts or change agents, affect its rate of adoption.
>
> (Rogers, 2003, p. 223)

This chapter presents the results of an assessment of the product development community at Sandia National Laboratories, where this research was conducted. The assessment served several purposes: (1) providing motivation for this research and guiding the design of the case study investigations presented in Chapters 6 and 7; (2) facilitating a longitudinal assessment of both demographics and attitudes toward FEA in the larger Sandia community, apart from the intervention activities of the case studies, which themselves combined to span a data collection period of approximately two years; and (3) demonstrating the extent to which the case study product development teams were representative of the larger Sandia population in terms of demographics and previous FEA exposure.

Section 3.1 describes the Context Assessment Survey (CAS), which was the primary method used to collect data for the assessment. Section 3.2 presents data on key demographic details and general familiarity with FEA. Section 3.3 presents a detailed summary of the findings, illustrating the range of opinions and past experiences with FEA that exist in the product development community at Sandia. Finally, Section 3.4 offers some reflection on the assessment results in light of the literature reviewed in Chapter 2.

3.1 Assessment Method

In order to assess the context for this longitudinal case study research, an online survey was used to collect data on past experiences and prevailing views of FEA at Sandia National Laboratories. A link to the survey was sent via email to approximately 150 Sandia employees in January 2012, near the beginning of the investigation, and again in January 2014, near the end. This survey pool was comprised of Sandia employees in various areas of product development and technical work. Most recipients of the survey link were employed at Sandia's site in Livermore, California, where the case study investigations occurred, but some invitations were also sent to individuals at Sandia's site in Albuquerque, New Mexico. To the extent possible, the pool was the same for the initial and closeout data sets, but it was not identical due to attrition and hiring of new employees over the two-year period. The timeline for the context data collection relative to the two case studies is shown in Figure 9. In the initial and closeout rounds of the survey, 67 and 55 responses were received, respectively.[3] The survey included questions in yes-no, multiple-choice, and short-answer format, and was 33 questions in length. However, not all questions were received by all respondents, due to the use of survey logic and some questions that were marked optional. The complete text of the FEA Context Assessment Survey (CAS) is included for reference in Appendix A.

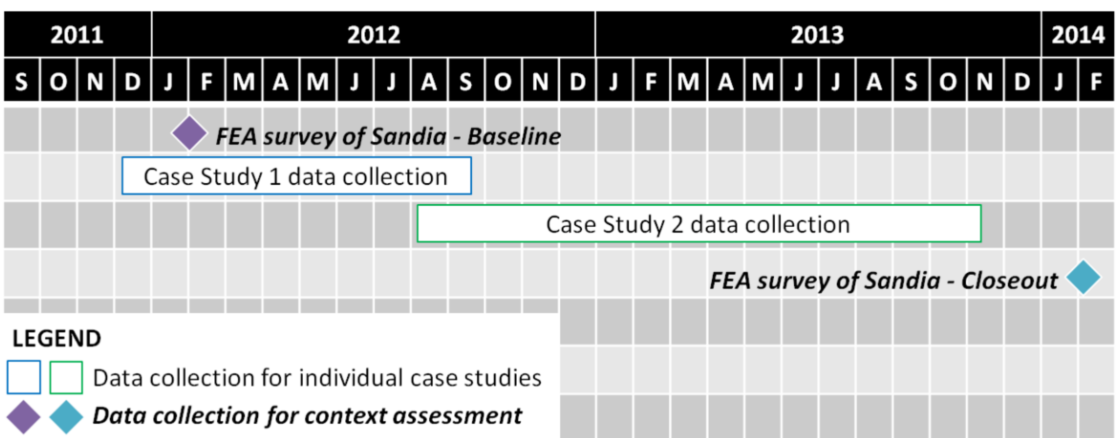


Figure 9: Timeline for Sandia context assessment with respect to case studies 1 and 2.
Data collection for the first and second case studies combined to span a period of approximately two years, from December 2011 through November 2013. Data collection for the context assessment spanned a similar two-year period, from January-February 2012 through January-February 2014.

[3] The online FEA survey was also used to assess the participants in the case studies, but these totals do not include the responses from the case study participants.

3.2 Demographics and FEA Exposure

The first intent of the context assessment was to investigate the product development community at Sandia National Laboratories in terms of demographics and general FEA exposure. This provided a means for demonstrating the extent to which the case study teams presented in Chapters 6 and 7 were representative of the wider Sandia product development community, in order to establish the external validity of the case study findings.

Survey respondents were asked about their technical background, present role, and length of time at Sandia. The results are shown and described in Table 4 and Table 5. The distributions of technical backgrounds and present roles did not change in a statistically-significant manner over the course of the two-year study. However, the distribution of responses to the question regarding length of time at Sandia did change in a statistically-significant manner, revealing both a general decrease in the percentage of employees who have been with Sandia for 26 years or more, and an increase in the percentage of employees who have been with Sandia for 5 years or less. This could reflect an overall shift toward a younger workforce and/or a shift away from Sandia's decades-old practice of hiring only new college graduates toward a practice of hiring professionals with industry experience.

Table 4: Degree field and roles in the Sandia product development community.
Results are shown for the Context Assessment Survey pre- and post-samplings. Categories with low numbers of responses were collapsed to a general 'other' category. For these data, which were collected using 'select all that apply' questions, the categorized responses were individually tested for significance at the P = 0.05 level using a chi-square test. None of the changes from pre- to post-samplings were significant at this level, suggesting that these demographics did not change significantly in the Sandia product development community over the course of the two-year study.

Survey Question	CAS-pre		CAS-post		P
	No.	%	No.	%	
What is your technical background or degree field? (Select all that apply.)					
Electrical engineering	32	47.8	25	45.5	0.80
Mechanical engineering	26	38.8	23	41.8	0.74
Other	15	22.4	10	18.2	0.57
What is your present role at Sandia? (Select all that apply.)					
Department manager	6	9.0	8	14.5	0.34
Electrical engineer	17	25.4	16	29.1	0.64
Mechanical engineer	19	28.4	16	29.1	0.93
Project lead	16	23.9	18	32.7	0.28
Systems engineer	20	29.9	15	27.3	0.75
Other	13	19.4	8	14.5	0.48

Table 5: Length of time at Sandia in the product development community.
Results are shown for the Context Assessment Survey pre- and post-samplings. The responses '16 to 20 years' and '21 to 25 years' were collapsed into one due to relatively low numbers of responses in these categories, which is likely attributable to a drop in hiring at Sandia during the 1990s. The biggest changes visible over the course of the two-year investigation include a relative increase in the number of people at Sandia for 5 years or less, and a relative increase in the number of people at Sandia for 26 years or more. These changes were tested for statistical significance using a chi-square test and were valid at the P = 0.05 level.

Survey Question	CAS-pre		CAS-post		P
	No.	%	No.	%	
How long have you worked at Sandia (or your current employer)?					
≤ 5 years	16	23.9	18	32.7	
6 - 10 years	13	19.4	8	14.5	
11 - 15 years	11	16.4	9	16.4	0.02
16 - 25 years	8	11.9	10	18.2	
≥ 26 years	19	28.4	10	18.2	
Total	67	100.0	55	100.0	---

Survey respondents were also asked about their exposure to FEA using several 'yes-no' questions, the results for which are shown in Table 6. Based on these data, overall exposure to FEA in the Sandia product development community did not change in a statistically-significant manner over the course of the two-year study.

Table 6: Exposure to FEA in the Sandia product development community.
Results are shown for the Context Assessment Survey pre- and post-samplings. The data were tested for significance at the P = 0.05 level using a chi-square test. None of the changes from pre- to post-samplings were significant at this level, suggesting that overall exposure to FEA did not change significantly in the Sandia product development community over the course of the two-year study.

Survey Question	CAS-pre		CAS-post		P
	No.	%	No.	%	
Have you ever seen FEA used on your past projects?					
Yes	58	86.6	51	92.7	0.27
No	9	13.4	4	7.3	
Have you ever used FEA software?					
Yes	26	38.8	29	52.7	0.12
No	41	61.2	26	47.3	
Have you ever taken a course on FEA?					
Yes	21	31.3	22	40.0	0.32
No	46	68.7	33	60.0	
Total	67	100.0	55	100.0	---

3.3 Views On FEA

A second intent of the context assessment was to investigate the prevailing attitudes toward FEA in the Sandia product development community. This served two key purposes: (1) providing motivation for this research and guiding the case study investigations, using the CAS data collected at the beginning of the investigation in January 2012; and (2) facilitating a longitudinal assessment of attitudes toward FEA in the larger Sandia community, apart from the intervention activities of the case studies presented in Chapters 6 and 7, by comparing the CAS data collected in January 2012 (CAS-pre) and January 2014 (CAS-post).

A glimpse into issues surrounding FEA is provided by a cursory examination of the quantitative survey question results, the most instructive of which are presented in Table 7. These data clearly reveal the prevalence of negative experiences with FEA: surprisingly high percentages of respondents indicated seeing instances when FEA was not beneficial, when FEA results were not presented in a clear and meaningful way, and when FEA results did not seem trustworthy or accurate. The length of time required to use FEA and the high dollar cost associated with its use are also reflected in the data. None of the changes over the course of the two-year study were statistically significant at the $P = 0.05$ level, suggesting that these views of FEA were the norm during the period of investigation. Table 8 presents a comparison of the results for two questions focused on the extent of FEA's influence in project execution and in the respondents' engineering intuition, also showing no statistically-significant changes over the two-year study.

Despite this lack of statistical significance between CAS-pre and CAS-post results, a subtle but interesting trend is discernable in the data. The CAS-post data show a slight decrease in the percentage of respondents observing 'positives' associated with FEA, such as FEA providing benefits to their projects, or the early use of FEA in the design process. On the other hand, the CAS-post data show a slightly greater percentage of respondents observing what might be collectively deemed 'negatives' views of FEA, such as FEA being unbeneficial or a hindrance to their projects; untrustworthy or inaccurate FEA results; FEA results that were unclear or not meaningful; and dollar cost or time required to use FEA being a factor. This trend is not significant at the $P = 0.05$ level, but instead shows up in the range of $P = 0.07$ to 0.09, depending on which survey questions are grouped in the collective bin of 'negatives'.

Table 7: Experiences with FEA in the Sandia product development community.
Results are shown for the Context Assessment Survey pre- and post-samplings. Due to survey logic, not all respondents received all questions; the 'valid percentage' is computed for each response by including only respondents who received that question. The data were tested for significance at the P = 0.05 level using a chi-square test. None of the changes were significant at this level. Overall, this suggests that the tension evident in these results, which is discussed further in this section, remained present within the Sandia product development community over the course of the two-year study.

	CAS-pre			CAS-post			
Survey Question	**No.**	**%**	**Valid %**	**No.**	**%**	**Valid %**	**P**
Seen the use of FEA be beneficial for a project?							
Yes	56	83.6	94.9	47	85.5	92.2	0.55
No	3	4.5	5.1	4	7.3	7.8	
Did not receive question	8	11.9	---	4	7.3	---	
Seen FEA used in a way that was not beneficial, or perhaps even a hindrance, to a project?							
Yes	28	41.8	47.5	31	56.4	60.8	0.16
No	31	46.3	52.5	20	36.4	39.2	
Did not receive question	8	11.9	---	4	7.3	---	
Seen FEA results presented that did not seem trustworthy or accurate?							
Yes	37	55.2	69.8	31	56.4	73.8	0.67
No	16	23.9	30.2	11	20.0	26.2	
Did not receive question	14	20.9	---	13	23.6	---	
Seen FEA results that were not explained in a way that was clear and meaningful?							
Yes	37	55.2	69.8	36	65.5	85.7	0.07
No	16	23.9	30.2	6	10.9	14.3	
Did not receive question	14	20.9	---	14	25.5	---	
Seen FEA used early on in the design process?							
Yes	40	59.7	80.0	28	50.9	71.8	0.37
No	10	14.9	20.0	11	20.0	28.2	
Did not receive question	17	25.4	---	16	29.1	---	
Seen FEA used in isolation from design activities?							
Yes	29	43.3	52.7	22	40.0	51.2	0.88
No	26	38.8	47.3	21	38.2	48.8	
Did not receive question	12	17.9	---	12	21.8	---	
Seen the cost of using FEA be a factor in deciding whether or not to use it?							
Yes	22	32.8	68.8	17	30.9	89.5	0.09
No	10	14.9	31.3	2	3.6	10.5	
Did not receive question	35	52.2	---	36	65.5	---	
Seen the time required to utilize FEA be a factor in deciding whether or not to use it?							
Yes	26	38.8	81.3	17	30.9	89.5	0.43
No	6	9.0	18.8	2	3.6	10.5	
Did not receive question	35	52.2	---	36	65.5	---	
Total	67	100.0	100.0	55	100.0	100.0	---

Table 8: Impact of FEA in the Sandia product development community.
Results are shown for the Context Assessment Survey pre- and post-samplings. Due to survey logic, not all respondents received all questions; the 'valid percentage' is computed for each response by including only respondents who received that question. The data were tested for significance at the P = 0.05 level using a chi-square test. None of the changes were significant at this level, suggesting that views of the relative impact of FEA did not change significantly in the Sandia product development community over the course of the two-year study.

Survey Question	CAS-pre No.	CAS-pre %	CAS-pre Valid %	CAS-post No.	CAS-post %	CAS-post Valid %	P
What areas of a project have you seen affected by the use of FEA? (Select all that apply.)							
Funding allocation	22	32.8	37.9	14	25.5	32.6	0.58
Requirements	48	71.6	82.8	38	69.1	88.4	0.43
Product design	40	59.7	69.0	29	52.7	67.4	0.87
Schedule planning	32	47.8	55.2	19	34.5	44.2	0.27
Qualification or testing	9	13.4	15.5	6	10.9	14.0	0.83
Other	3	4.5	5.2	2	3.6	4.7	0.90
Did not receive question	9	13.4	---	12	21.8	---	---
For mechanical design issues, what factors most influence your own engineering intuition? (Select all that apply.)							
Expert advice	42	62.7	84.0	29	52.7	74.4	0.26
Test/experimental results	45	67.2	90.0	36	65.5	92.3	0.71
Analysis/calculations	35	52.2	70.0	29	52.7	74.4	0.64
Design similarity	34	50.7	68.0	27	49.1	69.2	0.90
Other	2	3.0	4.0	3	5.5	7.7	0.45
Did not receive question	17	25.4	---	16	29.1	---	---

In addition to quantitative questions, the Context Assessment Survey also contained several short-answer questions that were designed to give respondents an opportunity to provide open-ended feedback on their views of FEA. A coding scheme, provided for reference in Appendix B, was developed based on the respondents' comments and was used to code the CAS-pre comment data. The data were heavily coded; essentially, only sensitive/proprietary comments and spurious (i.e., one-off) comments were excluded from coding. Double coding was intentionally kept to a minimum, with only about 11 percent of the CAS-pre comments double-coded. Related or contrasting codes were then grouped into eight main categories, forming an emergent taxonomy of the most common and contentious issues involved with the use of FEA in design and product development.

The CAS-post comment data were then coded using the same scheme. The addition of only one new code was required, and as the existing codes were applied and refined, the coded

CAS-pre data were reviewed to ensure consistent application. Double-coding was again kept to a minimum to the extent possible, with only about 14 percent of the CAS-post comments double-coded. Overall, the CAS-post results contained a larger number of write-in comments than did the CAS-pre results, but about 80 percent of that increase was accounted for by comments relating to just four of the eight general categories, as summarized in Table 9 using a related metric: the percentage of survey respondents that commented on each topic. These broad topics appear to have gained in visibility among the larger community over the course of this two-year study.

Table 9: Topics with large increases in the percentage of commenting respondents.
Percentages shown are for a total of 67 and 55 respondents in the CAS pre- and post-samplings, respectively. A noticeably larger percentage of the closeout survey respondents commented on advantages or disadvantages of FEA, complexity of design and FEA, integration with product development, and communication about FEA. The increase in feedback may suggest that these broad topics have gained in visibility among the larger community over the course of the two-year study.

General Category	CAS-pre		CAS-post	
	No.	%	No.	%
Advantages and Disadvantages of FEA	38	56.7	41	74.5
Complexity of FEA and Design	25	37.3	31	56.4
Integration of FEA with Product Design	24	35.8	29	52.7
Communication About FEA	15	22.4	22	40.0

A more detailed summary of the findings in each of the eight main coding categories is provided in the subsections below, including a quantitative comparison of the coded short-answer comments in the CAS-pre and CAS-post data. The underlying issues revealed by the Context Assessment Survey further demonstrate the motivation for this research and help illustrate the setting for the case study investigations presented in Chapters 6 and 7.

3.3.1 Advantages and Disadvantages of FEA

As shown in Table 7, the overwhelming majority of respondents indicated they had seen the use of FEA be beneficial to projects, but roughly half of these same respondents indicated they had also seen FEA used in a way that was not beneficial. The coded comment data shown in Table 10 further illustrate this mix of advantages and disadvantages presented by FEA. Respondents described FEA being beneficial for improving and optimizing designs, guiding design decisions, and identifying and analyzing weak points. But a substantial fraction of comments also described instances of FEA being improperly used or relying on poor assumptions, with many respondents providing first-hand accounts of FEA leading their development team astray on past projects. The distribution of comments in the CAS-pre and CAS-post data was very similar, as shown in Table 10. This suggests that no fundamental change occurred over the course of the study in terms of these widely recognized advantages and potential pitfalls of using FEA.

Table 10: Advantages provided by FEA vs. disadvantages when improperly used.
Percentages shown are for the total number of comments grouped in this category (66 and 85 for the CAS-pre and CAS-post, respectively). Comments underscore both the potential held by FEA to beneficially impact design and the risks associated with incorrect use.

Comment Code	CAS-pre		CAS-post	
	No.	%	No.	%
Improve or optimize product design, guide decisions	39	59.1	43	50.6
Identify and analyze weak points	11	16.7	18	21.2
Analyze system to define sub-component reqs.	2	3.0	5	5.9
Improperly used, poor assumptions, led team astray	14	21.2	19	22.4
Total	66	100.0	85	100.0

3.3.2 Dollar Cost of Using FEA

As shown in Table 7, only about half of the CAS-pre respondents received the question related to the cost of FEA—but of those that did, nearly 70 percent indicated they had seen cost be a factor when deciding whether or not to use it. That percentage increased to nearly 90 percent for the CAS-post respondents. The coded comment data shown in Table 11 illustrate a paradoxical view of the dollar cost associated with using FEA. About half of the cost-related comments in the CAS-pre data described how the use of FEA can reduce overall product development costs, while the other half plainly stated that using FEA costs too much. The same split is evident in the CAS-post data, along with the emergence of an interesting new theme. The idea that FEA is useful when the cost of experimental testing is prohibitive was a new theme that did not exist in the CAS-pre, even upon a second review. The appearance of this theme was matched primarily by a decrease in the percentage of comments that FEA costs too much, although some decrease in the percentage of comments that FEA can reduce costs was also evident. Taken together, these changes could be explained by an increased use of FEA to replace (rather than augment) experimental testing, which is a distinct possibility in Sandia product development activities. A second possible explanation is that in an era of tighter budgets, the use of FEA is being viewed less as an optional means of reducing costs, and more as a necessary measure to enable some level of design evaluation when reduced funding makes experimental testing infeasible.

Table 11: Tension in views over the dollar cost associated with using FEA.
Percentages shown are for the total number of comments grouped in this category (23 and 24 for the CAS-pre and CAS-post, respectively). The fundamental tension between the ideas that FEA can reduce cost and that FEA costs too much did not change over the course of the two-year study. The idea that FEA is useful when the cost of experimental testing is cost-prohibitive was a new theme that emerged in the CAS-post data.

Comment Code	CAS-pre		CAS-post	
	No.	%	No.	%
FEA can reduce cost	11	47.8	10	41.7
Useful when testing is cost-prohibitive	0	0.0	5	20.8
Dollar cost too high using FEA	12	52.2	9	37.5
Total	23	100.0	24	100.0

3.3.3 Time Required for FEA

As shown in Table 7, only about half of the CAS-pre respondents received the question related to the time required to utilize FEA—but of those that did, over 80 percent indicated they had seen time be a factor when deciding whether or not to use it. The percentage was similarly high for the CAS-post respondents at around 90 percent. The coded comment data shown in Table 12 illustrate the disagreement surrounding the issue of time. On the one hand, a large volume of comments cited an important reason for using FEA is the ability it provides to identify design issues early in development, and in doing so, to guide subsequent design activities. Other supportive comments indicated that FEA can save development time, and that FEA typically either leads or keeps pace with design activities. On the other hand, over one-third of the time-related comments in the CAS-pre data plainly indicated that FEA takes too long or that it typically lags design activities. The CAS-post data had a very similar distribution of time-related comments. This suggests that the underlying tension between the idea that FEA can be used beneficially within the time constraints of product development, and the idea that FEA takes too long to impact design, did not change over the course of the two-year study. Overall, the importance of the issue of time was underscored by the volume of comments it received, which was as much or more than any other category in both surveys.

Table 12: Disagreement about time-related benefits and drawbacks of using FEA.
Percentages shown are for the total number of comments grouped in this category (98 and 85 for the CAS-pre and CAS-post, respectively). The fundamental tension between the idea that FEA can be used beneficially within the time constraints of product development, and the idea that FEA takes too long to impact design, did not change over the course of the two-year study.

Comment Code	CAS-pre		CAS-post	
	No.	%	No.	%
Identify issues early, guide subsequent design	34	34.7	22	25.9
FEA typically keeps pace with design	13	13.3	11	12.9
FEA can save time	9	9.2	10	11.8
FEA typically leads design	5	5.1	6	7.1
FEA typically lags design	21	21.4	22	25.9
FEA takes too long	16	16.3	14	16.5
Total	98	100.0	85	100.0

3.3.4 Integration of FEA with Product Design

On this topic, the survey data did not point to any single, clearly-identifiable issue or disagreement, but rather revealed a complex topology of factors, as illustrated in Table 13. The most prevalent themes were the following:

- the importance of both the FEA analyst's knowledge of design details and project needs, and of maintaining a high degree of fidelity between FEA and design models;
- the importance of aligning the goals of FEA activities with project needs, and of clarifying scope, expectations, and deliverables for FEA;
- and the negative effect that performing FEA in isolation of product development activities has on the influence and applicability of FEA results. This appears to be an important issue, since just over half of both CAS-pre and CAS-post respondents who received the question indicated they have seen FEA used in isolation from design activities, as shown in Table 7.

The CAS-post data contained all of the same themes related to the integration of FEA with product design and development that were observed in the CAS-pre data. The only really substantial change was a decrease in the percentage of comments focusing on the need, when using FEA, to clarify the expectations, deliverables, and scope of FEA-related activities. Perhaps more noticeable than any changes in the other themes was the overall percentage of respondents that made comments related to the integration of FEA and product development, which increased from about 36 percent of CAS-pre respondents to about 53 percent of CAS-post respondents, as shown in Table 9.

Table 13: Variety of issues relating to the integration of FEA with product development.
Percentages shown are for the total number of comments grouped in this category (38 and 59 for the CAS-pre and CAS-post, respectively).

Comment Code	CAS-pre		CAS-post	
	No.	%	No.	%
Fidelity of FEA geometry and BCs vs. actual design	11	28.9	13	22.0
Analyst's knowledge of design details, project needs	8	21.1	14	23.7
FEA scope/deliverables must be clarified	7	18.4	3	5.1
Isolation reduces FEA's influence/applicability	5	13.2	10	16.9
FEA goals must be aligned with project needs	4	10.5	8	13.6
Growing integration of FEA and design software	2	5.3	5	8.5
Isolation enhances independent verification	1	2.6	6	10.2
Total	38	100.0	59	100.0

3.3.5 FEA in Design Thinking

An interesting contrast was evident in the data regarding the relative roles of FEA and engineering judgment. As shown in Table 14, about 28 percent of the CAS-pre comments described respondents' relying on FEA to inform and shape their engineering judgment, while 64 percent indicated that respondents trust their own engineering judgment over FEA results. A small fraction of comments frankly noted that FEA often does not provide any new knowledge. These same themes were also present in the CAS-post data, but the tension between trusting FEA to inform judgment vs. trusting engineering judgment over FEA was much more in equilibrium, with percentages of 48 and 46 percent, respectively. This may indicate a growing role for FEA over the course of the two year study. However, this apparent shift toward more reliance on FEA to inform thinking contrasts with the consistency across the CAS-pre and CAS-post shown in Table 8 for the influence of analysis in respondents' engineering intuition.

Table 14: Differing roles of FEA in the thinking of survey respondents.
Percentages shown are for the total number of comments grouped in this category (36 and 48 for the CAS-pre and CAS-post, respectively). The fundamental tension between the idea of using FEA to inform engineering judgment, vs. the inclination to trust engineering judgment over FEA results was present in both the CAS-pre and CAS-post data. However, a clear shift in the comment distribution was visible, possibly suggesting a growing role of FEA over the course of the two-year study.

Comment Code	CAS-pre		CAS-post	
	No.	%	No.	%
Trust FEA to inform judgment, scope problems	10	27.8	23	47.9
Use/trust judgment over FEA	23	63.9	22	45.8
FEA often provides no new knowledge	3	8.3	3	6.3
Total	36	100.0	48	100.0

3.3.6 Complexity of FEA and Design

As shown in Table 7, over two-thirds of the CAS-pre respondents that received the question indicated they had seen FEA results presented that did not seem trustworthy or accurate. The percentage was similarly high for the CAS-post respondents. The coded CAS-pre comment data shown in Table 15 illustrate the variety of themes related to complexity. A common theme was that FEA is highly dependent on the skill and/or credibility of the FEA analyst—an important point, but relatively neutral toward FEA itself. But a similar percentage of comments reflected a view that real problems encountered in engineering practice are too complex for FEA. As shown in Table 9, the percentage of respondents that commented on issues surrounding the complexity of FEA and/or design increased in the CAS-post data (56 percent) relative to the CAS-pre data (37 percent). In both datasets, about 60 percent of these comments were more negative toward FEA, although the dominant theme in the CAS-pre data—that real problems are either too complex, too ill-defined, or require too many assumptions for modeling with FEA—gave way in the CAS-post data to the theme that FEA results are too uncertain, not accurate, or not trustworthy. These themes may well be two manners of viewing the same fundamental issue.

Table 15: Variety of comments surrounding issues of complexity.
Percentages shown are for the total number of comments grouped in this category (45 and 66 for the CAS-pre and CAS-post, respectively). In both datasets, about 60 percent of comments were more negative toward FEA, although the dominant theme in the CAS-pre data—that real problems are either too complex, too ill-defined, or require too many assumptions for modeling with FEA—gave way in the CAS-post data to the theme that FEA results are too uncertain, not accurate, or not trustworthy. These themes may well be two manners of viewing the same fundamental issue.

Comment Code	CAS-pre		CAS-post	
	No.	%	No.	%
Dependent on skill/credibility of FEA analyst	17	37.8	22	33.3
FEA required by complexity of designs	1	2.2	5	7.6
Real problems too complex for FEA	19	42.2	8	12.1
FEA unnecessarily complicated	5	11.1	11	16.7
FEA results too uncertain, not accurate/trustworthy	3	6.7	20	30.3
Total	45	100.0	66	100.0

3.3.7 Testing vs. FEA

The importance of the respective roles of FEA and testing was underscored by the relatively high volume of comments received on the issue. Respondents cited a number of ways that FEA is beneficial: it complements experimental testing, can guide the design of experiments, can reduce the amount of physical testing required, and can be used to diagnose test failures. But a somewhat contrasting theme was by far the most common: that physical testing of experimental prototypes is required for validating FEA models. It is suspected that this fundamental tension—that FEA can benefit testing, but testing is generally required for validating FEA models—contributes largely to an overall lack of agreement and clarity in the product development community about how best to incorporate the use of FEA. The CAS-post data had a similar number of testing-related comments, and contained all of the same themes that were present in the CAS-pre data, suggesting that this underlying tension did not change over the course of the two-year study.

Table 16: Views that FEA benefits testing vs. the persistent need for validation testing.
Percentages shown are for the total number of comments grouped in this category (81 and 69 for the CAS-pre and CAS-post, respectively). The comments highlight a fundamental difficulty: that FEA can benefit testing, but testing is generally required for validating FEA models. The tension in these views may contribute to an overall lack of agreement and clarity in the product development community about how best to incorporate the use of FEA.

Comment Code	CAS-pre		CAS-post	
	No.	%	No.	%
Diagnose test failures	14	17.3	7	10.1
Reduce testing or design-test iterations	10	12.3	9	13.0
Complements experimental testing	10	12.3	9	13.0
Guides design of experiments	9	11.1	10	14.5
Testing required for model/results validation	38	46.9	34	49.3
Total	81	100.0	69	100.0

3.3.8 Communication About FEA

As shown in Table 7, about 70 percent of CAS-pre respondents indicated that they had seen FEA results that were not explained in a way that was clear and meaningful. The percentage was similarly high at over 85 percent for CAS-post respondents. The coded comment data further illustrated the importance of communication about FEA results, with the overwhelming majority in both the CAS-pre and CAS-post data focused on the need for improved communication about the details, assumptions, and limitations of FEA models. In particular, many comments emphasized the need for communication between the design team and the person(s) performing the FEA. As shown in Table 9, the percentage of CAS-pre survey respondents that commented about communication (22 percent) increased noticeably for the CAS-post respondents (40 percent), suggesting that recognition of the need for improved communication about FEA increased during the two-year study.

3.4 Comparison to Literature

This section concludes the Sandia Context Assessment with a reflection on selected topics from the Literature Review (Chapter 2). Section 3.4.1 maps the themes uncovered in the Context Assessment Survey to Rogers' five perceived attributes of an innovation (2003). Section 3.4.2 builds on the design process reviewed in Section 2.2 and presents a model of the product development process at Sandia. Section 3.4.3 briefly touches on the idea of organizational barriers discussed by Barley (1990).

3.4.1 Perceived Attributes of an Innovation

Rogers discussed the importance of the perceived attributes of an innovation in determining its rate of adoption (2003, p. 229-258). He described five attribute categories, which are shown in Table 3 and also compared to the findings from the Sandia Context Assessment Survey. For example, survey comments that ‘FEA costs too much’ or ‘FEA takes too long’ reflect a perception that FEA is not compatible with the resource constraints in real product development efforts. As another example, many survey comments emphasized that FEA is dependent on the skill of the user, and that real problems are often too complex for FEA. These are examples of the perceived complexity of using FEA. Finally, a substantial number of comments addressed the frequent need for validation testing when using FEA, which can be viewed as a perceived limitation on the ability to simply ‘try out FEA’ without a larger effort to plan for complementary experimental testing as part of the product development effort.

Table 17: Rogers’ perceived attributes (2003) compared to major CAS themes.
Rogers emphasized the importance that these perceived attributes have in determining an innovation’s rate of adoption. The categories of issues identified in the Sandia Context Assessment Survey map well into this framework, illustrating the relevance of Rogers’ prior work to the present investigation.

Perceived attributes of an innovation (Rogers, 2003, p. 229-258)	Mapping of issues identified in the Sandia Context Assessment Survey
Relative advantage *Is it better than the idea it supersedes?*	Advantages and disadvantages of FEA
Compatibility *Is it consistent with existing values, past experiences, and needs of potential adopters?*	Dollar cost of using FEA Time required for FEA Integration of FEA with product design
Complexity *Is it difficult to understand and use?*	FEA in design thinking Complexity of FEA and design
Trialability *Can it be experimented with on a limited basis?*	Testing vs. FEA
Observability *Are the results easily observed by, and communicated to, others?*	Communication about FEA

In the construct of Rogers’ overall model of the innovation-decision process (Figure 8), these issues of perception largely determine whether an individual forms a favorable or unfavorable view of an innovation. This ‘persuasion’ step in turn precedes their decision to adopt or reject the innovation. Addressing these negative or conflicting perceptions of FEA might be an effective and necessary step in diffusing its use into more product development efforts at Sandia, a goal consistent with the aims of Sandia management (Dimos, 2012).

3.4.2 Product Development Process at Sandia

At Sandia National Laboratories, the product development process often involves a system and sub-system architecture using an approach built around the 'Vee' model described by the International Council on Systems Engineering (2011, p. 27-31). However, the design of individual sub-systems or components can be described using a linear design process model such as those reviewed in Section 2.2. A simplified model of the product development process at Sandia is proffered in Figure 10. This model shares with most of those reviewed in Section 2.2 a generic reference to 'design evaluation', which may include analytical and/or experimental means. The decision of which type of evaluation to use (or whether to use both) is typically left to the discretion of the product development team, with input from customers and stakeholders.

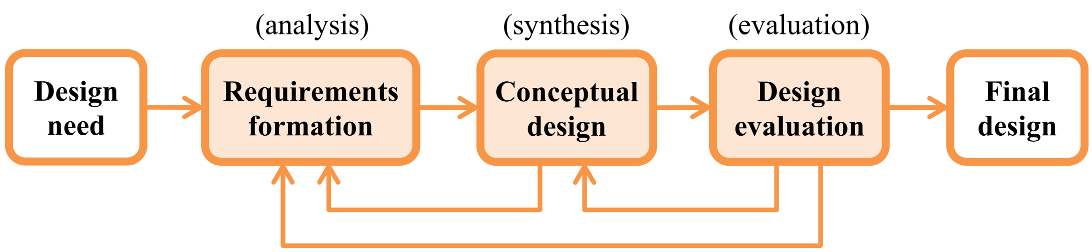


Figure 10: Product development process at Sandia National Laboratories.
This model contains the basic analysis-synthesis-evaluation elements, but with names that reflect the vernacular usage. Feedback loops show steps in the process that can be iterative. Design evaluation may include analytical and/or experimental means, at the discretion of the product development team and their customers and stakeholders.

This flexibility of approach is intended to empower product development teams to utilize resources (time, money, personnel) in a manner consistent with the needs and scope of their projects. However, given the conflicting views and variety of experiences revealed by the Context Assessment Survey, a more concerted effort to 'model' the use of FEA in product development may be warranted. The case study interventions described in Chapters 6 and 7 were designed with this in mind.

3.4.3 Organizational Barriers

While somewhat sinister-sounding, an element of macro-social forces may constrain the evolution and use of FEA technology in the product development community at Sandia, as articulated in the following quote from the CAS-pre survey.

> The single most important obstacle limiting the effective use of FEA is the separation of funding streams between the analysts and designers. A related obstacle is

> technology providers (code and tool developers) who don't understand (or want to understand) the needs of designers and whose goal is to preserve code and tool development funding, whether it will ultimately have product impact or not. At Sandia, the program structures of the last 20 years have created a sense of entitlement in the code and tool developer community, which has consumed resources that could have been used more effectively.
>
> Anonymous respondent, Sandia Context Assessment Survey (2012)

In any case, a designerly approach to using FEA, discussed further in Chapter 4, might go a long way toward reconciling the present state of the art with the lofty, long-held goals for FEA in product design and development.

4 Designerly FEA

> … there exists a designerly way of thinking and communicating that is both different from scientific and scholarly ways of thinking and communicating, and as powerful as scientific and scholarly methods of enquiry, when applied to its own kinds of problems.
>
> Archer (1979)

> … it is the design analyst who can, in the end, reap the greatest benefit from improved integration of simulation into the design process. … An analysis specialist is tasked primarily with calculating the behavior of a system with one or more specified parameters. He/she rarely has the freedom to stray beyond these parameters. A design analyst, on the other hand, typically defines the parameters on the fly while pursuing more tangible product goals. … In the hands of a designer, FEA truly becomes a powerful tool.
>
> Adams and Askenazi (1999, p. 355-356)

Many product design and development efforts warrant an approach to using FEA that overcomes the difficulties identified in the pilot research. This chapter introduces *designerly FEA*, a 'back-to-the-basics' approach to using FEA that aims to take advantage of enormous improvements in the usability of modern commercial FEA software combined with the horsepower of modern desktop computers to put FEA in the hands—and minds—of design engineers. It is proposed that a designerly approach to using FEA will contribute to meeting many of the identified goals for FEA in the realm of product development.

Section 4.1 provides an overview of basic concepts and terminology involved with using FEA. Section 4.2 outlines the tenets of a designerly approach to using FEA. Finally, Section 4.3 introduces the use of FEA in the design of ruggedized electronics packaging, which is the particular application explored in the case studies described in Chapters 6 and 7.

4.1 FEA Concept Inventory

This section briefly introduces a variety of concepts associated both with FEA in general, and with the particular use of FEA in the case studies (Chapters 6 and 7). This list is not meant to be exhaustive, but rather to serve as a primer for readers of this dissertation. In particular, these descriptions are intended to illustrate the variety of simplifications and assumptions that are involved with generating an FEA model of a structural design concept. For more information, a very accessible reference is the text by Adams and Askenazi (1999).

Geometry. The actual geometry of real-world parts and products can be exceedingly complex and nuanced. In most instances, FEA models are initially built beginning with CAD solid models, which often contain features that are unnecessary for any given FEA modeling task. The process of simplifying detailed design models—sometimes referred to as 'defeaturing'—typically involves removing such features, which can include small fillet radii, notches, holes, and/or various mechanical fasteners and hardware, etc.

Element types. In the field of FEA, a variety of element types exist (solids, shells, beams, links, etc.) along with various formulations of each (h-element, p-element, number of nodes, degrees of freedom at each node, etc.). These characteristics essentially define a set of capabilities and limitations for each element in terms of what types of deformation and other physical phenomena they can model, and building an FEA model involves selecting appropriate elements for the particular modeling task.

Mesh. The geometry of the part(s) to be analyzed must be discretized into elements, a process referred to as meshing. In the past, meshing was an arduous task that involved an enormous amount of very tedious work. Modern FEA software generally includes much better tools for generating meshes automatically, although the meshes achieved with automatic meshing algorithms are typically much less regular than those obtained with more manual techniques. In general, a certain amount of manual manipulation of automatic meshing tools is typically required.

Boundary conditions and loading. The part or assembly must be constrained in space and loaded in a manner that is representative of the real product. Loading refers to external forces, torques, bending moments, pressures, and/or displacements that result in a mechanical deformation of the product. Every modeling task is unique and can be legitimately performed using any one of a variety of approaches to constrain and load the model, with each approach likely presenting a combination of advantages and disadvantages.

Connections. When modeling an assembly of two or more parts, the parts must be connected together in a manner that is representative of the real product (which may utilize fasteners, welds, glue, press fits, etc.). Determining the best method for emulating such connections is not trivial and requires a deep understanding of both FEA and the product design being modeled. This issue is related to the issue of boundary conditions.

Material properties. Each element in the FEA model requires the assignment of a constitutive material model. Material models are a parameterization that approximates the observed real-world behavior of the material in response to various physical loading. Even for highly-accurate material models, the natural variation in the observed properties of a given material can be large and can contribute to the uncertainty associated with the FEA results.

Damping. For FEA models that explore the transient response of a design to external loading, the structural damping must be specified. Structural damping is akin to the damping ratio in a second-order single-degree-of-freedom mechanical system: it dictates the rate at which the perturbed system dissipates kinetic energy and returns to equilibrium. Damping is a highly empirical value that must be estimated based on existing data, and refined as-needed based on test data for the specific system. It is notoriously difficult to estimate a priori.

Non-linearities. A structure can exhibit non-linearity in its response to external loading for a variety of reasons, including the following: material nonlinearities, such as plasticity, hyper-elasticity, creep, and viscoelasticity; geometric nonlinearities, such as large strains, large displacements, and stress-stiffening; and boundary condition nonlinearities, such as contact and friction. Including non-linear behavior can increase the accuracy of a model, but comes at the expense of a significant increase in run times. A conscious decision must be made as to which, if any, potential sources of non-linearity to include in the model.

Measurement points. In an FEA model, points of specific interest may be specified ahead of time, at which more extensive (and time-consuming) calculations are performed to fully characterize the structural response. This is analogous to deciding what types of instrumentation to use in a structural mechanics experiment (i.e., strain gages, accelerometers, etc.), where to place them, how many to use, etc.

Model validation. The terms *verification* and *validation* are widely used in the scientific and engineering communities, often acquiring differing and even conflicting definitions and connotations. For the purpose of this research, validation refers to the process of acquiring experimental data that is used to demonstrate the degree to which an FEA model accurately predicts the phenomenon of interest.

4.2 Tenets of Designerly FEA

The following tenets outline a designerly approach to using FEA in the product development process. Where possible, they are supported with references to extant literature (Chapter 2) or themes from the Sandia Context Assessment (Chapter 3). These ideas are essentially explored as hypotheses in the case studies described in Chapters 6 and 7.

Section 4.2.1 reviews the principle of keeping FEA models as simple as possible, in order to promote improved turn-around time. Section 4.2.2 discusses the use of designer-friendly FEA software, which is increasingly well-integrated with solid modeling design software. Section 4.2.3 describes the importance of making the FEA analyst a fully-embedded member of the product development team. Section 4.2.4 discusses the use of FEA for exploring relative comparisons of design options, an inherently 'designerly' way of utilizing FEA. Finally, Section 4.2.5 describes an approach whereby the first physical prototype test is utilized as an opportunity for gathering experimental data to validate and refine the FEA model.

4.2.1 Simplified FEA Models

In general, FEA models should be kept as simple as possible for the analysis task at hand—for example, in terms of geometry, element types, boundary and loading conditions, inclusion of non-linearities, etc. Keeping FEA models simple saves time in terms of model setup, running, and debugging, thereby promoting overall faster turn-around times to support the use of FEA in the design process. This use of simplified FEA models dovetails especially well with conceptual design activities, in terms of both (1) the sufficiency of approximate geometry definitions for the types of analyses required, and (2) the lack of available detailed design geometry, which does not exist at this point in the design process (Högberg, 2001; Schelkle and Elsenhans, 2001; Donders et al., 2009). A corollary to this is avoiding the common misconception that if an analysis of a simplified model provides some benefit, then an analysis with every possible design feature and detail must provide more benefit. (Adams, 2006, p. 5).

In reality, the principle of using simplified FEA models to the extent possible has existed for a long time, but has been easy to lose sight of given the enormous improvements in computational speeds that have occurred over the decades (Osborne and Prater, 2010). Knowing how much detail and complexity to include requires a general understanding of FEA as well as an intimate understanding of which design details matter for the particular design question(s) being asked. Achieving this proper balance of fidelity between FEA and design models thus relies on a strong integration of FEA and product design activities, a theme that emerged in the Sandia Context Assessment (Section 3.3.4).

An important caveat to this general principle applies when an FEA model is being generated from a detailed design model. The reduced run time and [potentially] reduced debugging time offered by a simpler FEA model must be weighed against the time required to defeature the detailed design model, which can be substantial. As a simple rule of thumb, when considering the merit of implementing any particular simplification, Adams and Askenazi recommend that the run time saved over the life of the FEA model be four or more times greater than the amount of time required to implement the simplification (1999, p. 200).

4.2.2 Designer-Friendly FEA Software

The emergence in recent years of commercial FEA software targeted at design engineers presents an excellent opportunity to more fully integrate FEA into the core of the design process. As mentioned in Section 1.2, Sandia National Laboratories has created a large number of extremely capable FEA codes for analyzing a variety of complex phenomena. But for several of the most common categories of problems that arise in product development (i.e., linear problems in stress analysis, structural dynamics, heat transfer, etc.), commercial codes are generally much easier and more intuitive for design engineers to use.

For example, in the case study investigations described in Chapters 6 and 7, the FEA was performed using Mechanica, the integrated FEA software available with Pro/Engineer solid modeling design software.[4] Mechanica lacks many of the extensive analysis capabilities of the more traditional commercial codes (such as Nastran, Ansys, and Abaqus), and it is not widely

[4] Mechanica is now Creo Simulate, and Pro/Engineer Wildfire is now Creo Parametric. Both are made by Parametric Technology Corporation.

used by expert, full-time analysts at Sandia. But it has well-developed tools for automatic meshing, and is extremely well-integrated with the parametric solid modeling tools of Pro/Engineer, which is used at Sandia for much of its product design and development activities. In many ways, Mechanica exemplifies the culmination of early efforts by Shephard and Yerry (1986), Rudd (1988), and many others.

In order to achieve this improved integration with design software, the creators of Mechanica have relied on some strategic compromises. For example, Mechanica utilizes tetrahedral elements rather than hexahedral elements. Some disagreement exists within the FEA community as to the merits of all-tetrahedral meshes (e.g., Cifuentes and Kalbag, 1992; Benzley et al., 1995; Adams and Askenazi, 1999, p. 153-154; Tautges, 2001), as hexahedral elements are generally regarded as offering all-around superior performance. This seems to be the dominant view within the analysis community at Sandia. However, tetrahedral elements are much more conducive to implementation in automatic meshing routines (Cifuentes and Kalbag, 1992; Adams and Askenazi, 1999, p. 322), which dramatically decreases the amount of time required generate a meshed model.

Additionally, Mechanica is a p-element code, as opposed to the more traditional h-element formulation used by most FEA software. The difference between these FEA techniques is in how convergence is achieved. With h-element codes, the element density is increased in regions of high stress gradients until convergence of the solution is achieved to within some specified criteria. Often the mesh must be refined manually by the user. On the other hand, with p-element codes such as Mechanica, convergence is achieved by increasing the polynomial order of the elements in the regions of high stress gradients, which means the mesh itself does not need to be modified to iterate toward convergence. Whereas h-element codes typically use second-order elements, Mechanica initiates analyses with third-order elements, allowing it to tolerate much more irregularity in the mesh than can be tolerated in a comparable h-element model.

The use of Mechanica is not referenced heavily in published literature, likely due to its marketing position as a tool for design engineers rather than a feature-heavy tool for full-time analysts; a few published examples include Pankoke et al. (1998), Bamberg (2000), Högberg (2001), Maniar et al. (2009), Park et al. (2010), Oyelami et al. (2012), and Semrád (2013). Despite any real (or perceived) performance limitations, the result of coupling the use of tetrahedral elements, automatic meshing, and p-element technology is a rather dramatic reduction in the time and effort required to iterate from a design concept, to meshed geometry, to a completed analysis, and back again to a refined design concept. As such, for the classes of problems that fall within its capabilities, Mechanica affords design engineers the opportunity to enfold the use of FEA into their product development activities while minimizing the additional time required. The importance of this was underscored by the Context Assessment, as using FEA to identify issues early in the design process was a widely-recognized benefit, yet a large contingent of Sandia's product development community noted FEA taking too long or tending to lag design activities.

4.2.3 FEA Analyst an Integral Member of the Design Team

In many large companies, such as in the aerospace and automotive industries, FEA is performed by full-time analysts who are in different organizations than the responsible design engineers. Such a division has also been the norm within Sandia and persists to this day. This concentration of FEA expertise fosters a strong FEA community and growth of FEA analysts in terms of their technical expertise, but at a cost of posing a strain on the integration of analysis and design activities. Toupin (2008a,b) points to a trend away from this traditional division in the automotive industry, with a move toward design engineers performing much of their own analysis using commercial FEA software.

In order to maximize the potential for FEA to impact product development activities and decision-making, the individual performing the FEA should be a full-fledged member of the design team, with all the privileges and responsibilities contained therein. This not only facilities effective communication between the FEA analyst and the responsible design engineers, but also aids in ensuring a critical alignment of FEA goals and activities with the most pressing needs of the product development team—both of which were concerns expressed by respondents in the Sandia Context Assessment (Sections 3.3.8 and 3.3.4, respectively). The importance of this cannot be understated, since these needs are neither static nor easy to predict, but rather tend to evolve over the course of a product development effort. Because of this, using FEA expertly and optimally in product development requires a thorough understanding of design needs, the capabilities (and limitations) of FEA to address those needs, and the time and effort required to do so.

Ideally, the individual performing the FEA should be co-located with the product development team. Residing together may help facilitate more understanding of the product design and project needs on the part of the analyst, who in turn can help the team make better use of FEA as a tool to supplement and guide their design thinking. Conversely, working closely and regularly with an experienced FEA user may help other members of the product development team develop a better understanding of the strengths and limitations of FEA, and how best to utilize it in product development. Additionally, embedding and co-locating the FEA analyst with the product development team may provide a better platform for the analyst to establish their credibility with the team, which was an important theme that emerged in the Context Assessment (Section 3.3.6).

4.2.4 FEA for Relative Comparisons

Design engineers are often confronted with the need to decide between multiple design options. They are also faced with many 'small' design decisions that involve understanding what makes a design better or worse in terms of some design parameter that is known to be important (e.g., for functionality, reliability, robustness, human factors, aesthetics, etc.) but that has not been developed into a formal design requirement or performance specification. Such scenarios present an excellent opportunity to use FEA early in the design process for relative comparisons of design options, to inform decision-making and design understanding. Moreover, there can be a natural 'canceling out' of certain types of inaccuracies and uncertainties in FEA results when similar design options are compared in a relative manner, and the same types of inaccuracies and uncertainties are present in each (e.g., boundary conditions, material properties, damping ratios, etc.). This can be an effective technique for overcoming the inaccuracy and uncertainty associated with FEA results, and for addressing real design problems that are complex, ill-defined, and require many assumptions—which were strong themes in the Sandia Context Assessment (Section 3.3.6).

It is important to remain cognizant of this class of questions for FEA, in contrast with the somewhat more natural and prevalent tendency to conceive of questions for FEA that require an absolute answer. Schelkle and Elsenhans (2001) contrasted these two distinct uses of FEA in the context of the automobile design process, noting that "In the concept phase of a new car project, CAE mainly serves to calculate the overall structural behavior of the car… which… should be calculated in a sufficiently precise manner (relative statements)." Later in the development cycle, "… CAE calculation performed in the series development phase must be very reliable (absolute statements)." In other words, a natural connection exists between the use of simple models with a relatively high degree of uncertainty to answer relative questions, and the ability to successfully utilize FEA early in the design process.

4.2.5 First Physical Prototype Test to Validate FEA

Most types of products eventually undergo physical prototype testing as part of the ‘evaluation’ step of the design process. With a little effort and foresight, such testing can often be used as an opportunity to gather experimental data for validating and refining FEA models developed during conceptual design activities. For example, in the product development process at Sandia National Laboratories (Figure 10), such an implementation of FEA might look something like the process depicted in Figure 11.

To be clear, the purpose of a “go/no-go” prototype test and the experimental data needed to validate the most uncertain aspects of an FEA model might lead to test setups that are simply too different to be incorporated into one. But in many instances, there is enough overlap between the two needs that a unified approach is worth considering. It may be that a handful of additional measurements, measurement types (strain gages, accelerometers, temperature sensors, etc.), or [non-destructive] test runs would go a long way toward demonstrating—and helping to improve—the accuracy of an early FEA model.

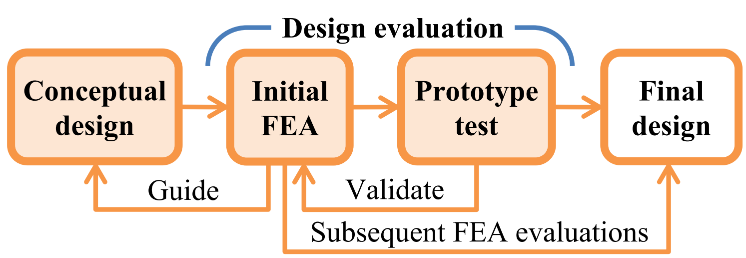


Figure 11: FEA in product development, validated using first physical prototype test.
Used in this manner, initial FEA modeling supports conceptual design activities and decision-making. Testing of a first physical prototype is leveraged to collect experimental data for validating the initial FEA model, which can in turn be used, when needed, to augment limited experimental data and/or to guide subsequent design decisions as product development continues.

Finally, the validated FEA model can be used to guide subsequent design decisions and adjustments as the product development process continues. Overall, this approach helps to address some of the tension that was evident in the results of the Sandia Context Assessment (Section 3.3.7), by clarifying that (1) the goal of using FEA does not have to be the outright elimination of testing, and (2) the need for experimental testing to validate FEA models does not nullify the value that FEA can provide. Rather, the intent is to take a balanced view of the value of each, leveraging routine testing activities into a validated FEA model that supplements and enriches the limited amount of data that can be collected in testing.

4.3 Application: Dynamic Response of Electronics Packaging

The case study design projects covered in Chapters 6 and 7 are both taken from the area of designing mechanical packaging for ruggedized electronics. Severe vibration and shock environments encountered during field conditions typically represent a driving factor for this class of products. Resonant frequencies of the circuit boards and their mechanical packaging structure (housings, mounting plates, brackets, etc.) are often excited by vibration and shock inputs. This can result in damaging stress levels and eventual fatigue failure of delicate electrical solder joints, which may in turn cause malfunction or premature failure of the electronics. As part of an overall effort to ensure the quality and ruggedness of the system, it therefore becomes crucial to take into consideration the dynamic response of the circuit boards and their mechanical packaging. Popular references on the subject include Pecht (1991) and Steinberg (2000). Hadim and Suwa (2008) briefly mention this topic as part of a comprehensive overview of the state-of-the-art in electronics packaging design. More recent overviews from trade literature have been provided by GE Intelligent Platforms (2010) and Southwork (2012).

Unfortunately, an understanding of dynamic response issues is often not developed unless failures or anomalous behavior are encountered during laboratory testing of functional prototypes, thus forcing a detailed investigation late in the product development cycle.[5] When these situations occur, FEA is often used to build detailed models of the packaging design, which can then be used to diagnose the problem and explore design fixes. Examples from this and other fields of using FEA as a diagnostic tool to troubleshoot dynamic response issues pervade the literature (e.g., Maly, 1996; Rossin et al., 2006; Živanović et al., 2007; Stanko et al., 2008; Yue-min et al., 2009). While powerful in its own right, diagnosing test failures is only one manner of using FEA.

[5] This has not been an uncommon occurrence at Sandia National Laboratories, California, where this research investigation was conducted. In an informal survey of 10 present and former electronics packaging design engineers, who discussed a total of 25 different products covering a roughly 15-year period from about 1995 to 2010, 11 of the products were recollected to have encountered problems during vibration and shock testing. In each of these instances, the problems encountered in testing included one or more of the following: resonance of mechanical housings and mounting plates, flexure of circuit boards at resonance, mechanical or internal failure of electrical/electronic components, and/or failure of mechanical mounting hardware. The most common solutions to these problems included mechanical redesigns (usually minor, but sometimes major), local application of epoxy or potting to minimize deflections and protect solder joints, and/or negotiating reduced vibration and shock requirements with customers.

4.3.1 Designerly FEA for Electronics Packaging Design

An understanding of a design's dynamic response is arguably of the most benefit early in the development process, when design changes are of lower consequence. In these early stages, estimates of circuit board dynamic response can be used for tailoring the packaging design to avoid resonances at or near frequencies where strong input will be encountered in the field. Characterizing the natural frequencies of circuit boards and the various mechanical housings and enclosures can also be used to ensure adequate separation between their natural frequencies, which helps to reduce the occurrence of severe resonances (Steinberg, 2000, p. 150-165). In addition, response estimates can be used to ensure that the circuit board and mechanical packaging design will not result in the required circuit board electrical components being subjected to any known vibration or shock survivability limits. Laird (2008a,b,c) provided a very readable summary of how FEA techniques such as these can be used as part of the design process in a variety of fields to minimize the occurrence of destructive resonances.

Simplified techniques for modeling large electrical components, mounting hardware, and even entire packaging designs are useful elements of a designerly approach to using FEA for dynamic response evaluation, as shown on the left half of Figure 12. This application of FEA is a natural fit for the earlier stages of the design process, since it requires much less geometric detail than a comparable stress analysis. Moreover, the use of simplified models ensures that the time required to both develop and run the models is minimized. The case study investigations described in Chapters 6 and 7 apply designerly FEA for this type of early-stage evaluation of dynamic response.

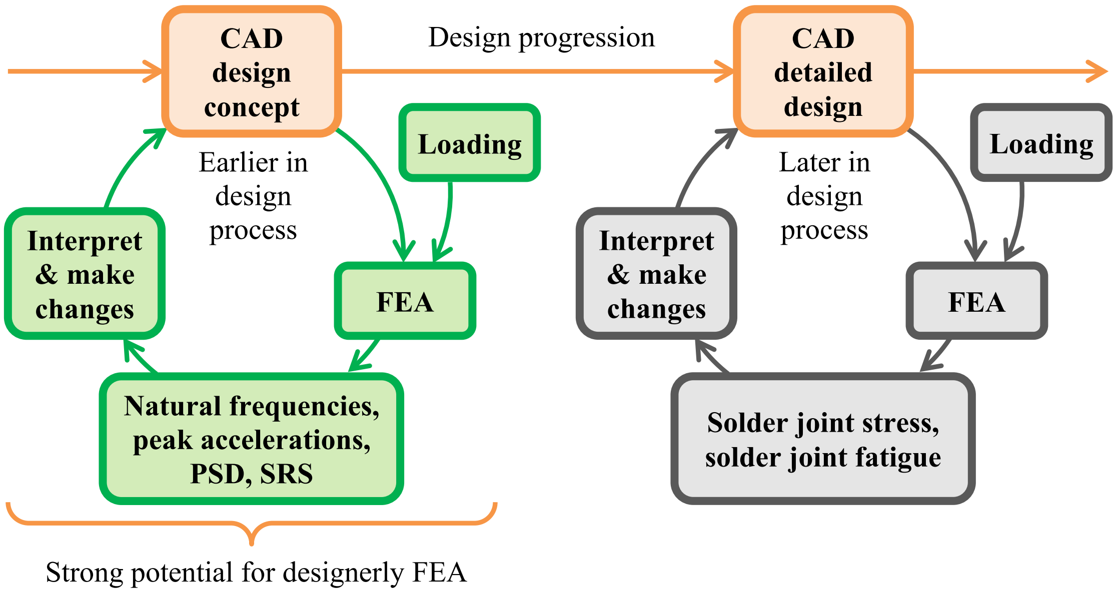


Figure 12: Contrasting early- and late-stage FEA of electronics packaging designs.
The use of FEA for stress analysis to predict failure of ruggedized electronics is shown on the right. This type of analysis requires detailed product definition down to individual solder joints, and is therefore difficult to do early in the design process. The use of FEA to evaluate the dynamic response of a packaging design is shown on the left. This type of FEA can utilize less-detailed models, such as those available early in conceptual design, which is when such evaluations are most useful. This technique does not directly predict product failure by modeling stress in solder joints. Rather, the dynamic response characteristics are used as indicators of good or bad design. The technique relies heavily on engineering judgment.

4.3.2 Previous Applications of FEA to Circuit Board Dynamic Response Modeling

The recent literature is full of examples of using FEA to model the response of circuit boards to vibration and/or shock inputs, each with its own focus on a particular part of the overall modeling task. Some authors have focused on deriving accurate estimates for the effective bulk (i.e., simplified) material properties of either multi-layered circuit boards (Oh et al., 2006; Wang et al., 2006; Lee et al., 2008) or large connectors and electrical components on the circuit boards (Pitarresi et al., 2004). Others have examined the mounting hardware used to secure the circuit boards and the appropriate FEA boundary conditions for capturing those effects (Park et al., 2007a,b). Yet others have focused on including geometric detail down to dozens of individual solder balls on each chip package in order to predict maximum stresses for developing solder joint reliability models (Luan and Tee, 2005; Tee et al., 2005; Liu et al., 2008). In each of these efforts, FEA was used to simulate a test setup involving an individual circuit board, as opposed to a complete product design including, e.g., realistic product housings and/or multiple circuit boards. An exception to this was the work by Kim and Park (2004), which stands out as an instructive example of modeling a complete product design (a cellular phone) and successfully matching experimental results, while nonetheless relying on linear material models that were estimated a priori.

Some of these previous efforts are more applicable for FEA stress analysis performed late in the product development cycle, when detailed design definitions exist—especially those focused on stress analysis of solder joints on particular chip packages. This type of analysis is depicted on the right half of Figure 12.

4.3.3 Alternatives to Using FEA for Electronics Packaging Design

It should be noted that FEA is not the only means to accomplish these early design evaluations. Closed-form equations can be used to very roughly estimate the natural frequencies and responses of structural components and circuit boards by identifying and approximating the most fundamental geometries in the product design. Steinberg (2000) covers these techniques in great detail. In practice, however, this type of analysis is not routinely performed by design engineers in the setting where the case studies were conducted. Instead, a heavy reliance exists on both a design-build-test philosophy and the use of previous successful designs to guide the intuition of the responsible design engineer.

Many other industries already use a combination of prototype testing and FEA (or other simulation technologies) because the cost and time associated with obtaining and testing certain classes of products is prohibitive. In such instances, although the accuracy of even the most advanced simulation technologies is still limited, design engineers are often forced to rely on FEA because 'something is better than nothing' when design-build-test iterations must be absolutely minimized. This is the case, for example, with civil engineering structures (buildings, bridges, etc.), which are subject to wind loading and earthquakes; automobile designs, which must undergo crashworthiness testing; satellites and other space systems, which are often built in quantities of no more than one or two; and other applications involving system-level testing of complex physical phenomena and/or products with very long manufacturing lead times.

In contrast, functional prototypes of circuit boards and their mechanical packaging designs are relatively quick and inexpensive to obtain, and vibration/shock testing is relatively easy to perform (and is in fact 'required' to be performed as a matter of routine development). As such, it is difficult for FEA to gain a foothold alongside the more established design-build-test iterative approach.

5 Research Methodology

> The reflective researcher cannot maintain distance from, much less superiority to, the experience of practice. … He must somehow gain an inside view of the experience of practice.
>
> Schön (1983, p. 323)

The goal of this research was to investigate how the use of designerly FEA on real design projects might help overcome the negative perceptions and resistance to FEA that exist in the product development community. To accomplish this, qualitative case-study research was conducted as part of two product design efforts at Sandia National Laboratories. This chapter provides an overview of the research methodology.

Sections 5.1 and 5.2 describe the case study construct and participant-observation by the investigator. Section 5.3 describes the data collection methods, which included surveys, interviews, and case study field notes. Section 5.4 delineates the main and embedded units of analysis for the study. Section 5.5 describes the intervention and communication strategy. Section 5.6 explains the qualitative analysis method that was used to interpret the case study data. Finally, Section 5.7 includes a brief note on the required Institutional Review Board (IRB) approvals, and Section 5.8 reviews limitations of this methodology.

5.1 Case Study Research with Two-Case Design

The research approach was built around the case study method (Eisenhardt, 1989; Yin, 2009). Yin defines a case study as "an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (2009, p. 18). He further notes that "the case study method allows investigators to retain the holistic and meaningful characteristics of real-life events—such as… small group behavior, organizational and managerial processes… and the maturation of industries." This nature of the case study method made it well-suited to explore this research topic, as described below.

The research was conducted as part of two product design and development efforts, each of which was treated as a separate case study. The intent was to construct a multiple-case study framework utilizing replication logic to strengthen the findings (Eisenhardt, 1989; Yin, 2009, p. 54-58). Replication logic stands in contrast to the more widely understood idea of sampling logic, in which the rules of inferential statistics are used to generalize findings to populations and establish confidence intervals. The intent with replication logic is either to duplicate the results of a previous experiment (known as a literal replication), or to achieve contrasting results for a predictable reason (known as a theoretical replication) (Yin, 2009, p. 54). In other words, a case study does not represent an individual 'sample' within an experiment, but rather is analogous to an entire experiment. Replication of results across multiple cases can therefore strengthen findings in much the same manner as replicating (or confirming) the results from one experiment using a follow-on experiment.

Related to the use of replication logic is the concept of theoretical sampling for case selection (Eisenhardt, 1989; Yin, 2009, p. 54-58). The intent is to select cases using a strategy in which characteristics of the situation that are deemed significant are either held consistent or deliberately varied—much in the same manner that one selects the characteristics of an experiment. In the present investigation, the two cases were selected based on a number of characteristics that they shared.

- Each product design was from a class of products that could benefit substantially from the use of FEA, as described in Section 4.3.

- Each project was from a product area at Sandia that allows product development teams to perform design, analysis, and testing efforts with a fair amount of flexibility and room to innovate (Section 3.4.2).
- Each project had a reasonably high likelihood of being carried through from concept development to prototype testing.
- Each project was expected to be relatively fast-paced and progress from concept development through analysis, detailed design, prototype fabrication, and testing in approximately one year (Figure 9).
- Each project presented the investigator with the opportunity to participate on the product development teams.

On the other hand, the two case studies differed in but a few very notable and important ways.

- The first case was a modification of an existing design, so much of the development work carried with it a fair amount of design knowledge and confidence based on the predecessor design.
- The second case was a new structural design and included the development of major subcomponents. It was more aggressive overall in terms of volume constraints, achievable circuit board area, and thermal management issues.

An overview of the two-case research design is shown for reference in Table 18, and is discussed more in the following sections.

Table 18: Two-case research design with participants as embedded units of analysis.

	Case Study 1	**Case Study 2**
Context	Sandia National Laboratories	Sandia National Laboratories
Design project (“case”, or main unit of analysis)	Modification of existing design; 3 concepts analyzed	New, aggressive design; 1 concept analyzed
Study participants (embedded unit of analysis)	9 participants	7 participants
Investigator role (participant-observer for each case)	FEA analyst; mechanical design engineer on predecessor design	Mechanical design engineer and FEA analyst

5.2 Reflective Research as a Participant-Observer

The research investigator was an integral member of each product development team and assumed a role of participant-observer to conduct this investigation. Yin notes that this research technique offers distinct advantages—namely, "the ability to gain access to events or groups that are otherwise inaccessible to a study," and "the ability to perceive reality from the viewpoint of someone 'inside' the case study rather than external to it" (2009, p. 112).

In the first case study, the investigator was the FEA analyst for the project, but the role of lead mechanical design engineer was held by another design team member. However, the investigator had been the lead design engineer on a predecessor design, and so was very familiar with the details and nuances of the various design concepts under consideration. In the second case study, the investigator was both the lead mechanical design engineer and the FEA analyst for the project. For both projects, the investigator led the effort to ensure that the FEA and the physical prototype testing activities were complementary. It should also be emphasized that the investigator was already experienced in the area of packaging design for ruggedized electronics, and was *not* simply an FEA analyst 'brought in' to implement the use of FEA for a class of products with which he was unfamiliar.

While somewhat unconventional, this participant-observer case study research approach was cast in the spirit of the ideas put forth by Schön (1983), who decades ago predicted a rising interest and openness to various types of 'reflective' research.

> In the kinds of reflective research I have outlined, researchers and practitioners enter into modes of collaboration very different from the forms of exchange envisaged under the model of applied science. … The reflective researcher cannot maintain distance from, much less superiority to, the experience of practice. … He must somehow gain an inside view of the experience of practice. … The researcher may stand to the practitioner in a relationship of participant-observation. The practitioner may take time out to become a reflective researcher, moving in and out of research and practice careers. … University faculty will become interested in professional practice, not only as a source of problems for study or internships for students, but as a source of access to reflective practice. … Conversely, practice institutions may come to see themselves increasingly as centers of research and education. Engineering groups… may recognize the reflection-in-action of their members and make a place for the reflective research which will support it. … The roles of practitioner and researcher will have permeable boundaries, and research and practice careers will intertwine as a matter of course.
>
> Schön (1983, p. 323-325)

Overall, the method used in this investigation also bears similarities to the idea of action research, as described by Kemmis et al. (1988) and summarized by Case and Light (2007). In essence, action research is demarked by the following: a focus on improving practice within the everyday contexts that the practice occurs; the existence of a plan (an idea) to improve practice; and active participation of other practitioners—rather than just the primary researcher—to implement the plan, observe the effects, and iteratively improve and re-implement the plan of action. The present research might better fit this description if it included, e.g., a deliberate focus on having other design team members participate in using FEA themselves.

5.3 Mixed-Method Data Collection with Longitudinal Dimension

A key strength of the case study research method is its reliance on multiple approaches to data collection. The aim is to achieve convergence of the data in a "triangulating" fashion, in order to better substantiate the findings and strengthen the overall construct validity of the research (Eisenhardt, 1989; Yin, 2009, p. 114-117). The present investigation utilized surveys, interviews, and notes from personal conversations to collect data on how exposure to designerly FEA impacted the participants' general views and perceptions of FEA. These data were collected over time, as each case study project progressed, giving a longitudinal dimension to each case. An overview of the survey and interview data collection methods for the two case studies is shown for reference in Table 19.

Survey data were collected using the same online survey used for the Sandia Context Assessment, as described in Chapter 3. The survey focused on respondents' overall experiences with FEA: their past exposure to FEA, experiences with it, views of its benefits and limitations, and opinions on how it should and should not be used. The survey was intended to capture a 'baseline' reading on each participant at the onset of their involvement in the case study projects. Participants in the first case study took the FEA survey near the beginning of the first project. Participants 12 and 13 (who were only involved in the second case study) took the survey near the beginning of the second project. The survey included questions in yes-no, multiple-choice, and short-answer format, and was 33 questions in length. However, not all questions were received by all respondents, due to the use of survey logic and some questions that were marked optional. The FEA survey questions are included for reference in Appendix A.

Table 19: Data collection methods and timeline, showing participants in each case study.
Case study 1 included nine participants and relied on data collected using the survey, the 1st round of interviews, and field notes. Case study 2 included seven participants and relied on data collected using the 1st and 2nd rounds of interviews, the survey (for participants 12 and 13 only), and field notes. The Sandia Context Assessment (described in Chapter 3) relied on data collected using the same survey, submitted two years apart to a large pool of Sandia employees.

			Time →			
Participant No.			**FEA survey Dec 2011-Feb 2012**	**1st FEA interview Aug-Sep 2012**	**2nd FEA interview Oct-Nov 2013**	**FEA survey Jan-Feb 2014**
2	●		✓	✓		
5	●		✓	✓		
6	●		✓	✓		
9	●		✓	✓		
1	●	●	✓	✓	✓	
4	●	●	✓	✓	✓	
7	●	●	✓	✓	✓	
8	●	●	✓	✓	✓	
11	●	●	✓	✓	✓	
12		●		FEA survey 4/2013	✓	
13		●		FEA survey 4/2013	✓	
Sandia CAS			✓			✓

Legend:

- ● Participant in case study 1
- ● Participant in case study 2
- Case study 1 data
- Case study 2 data
- Data for context assessment

Note: Participant numbers 3 and 10 were assigned to individuals who left the study shortly after its inception, due to a job change and limited availability, respectively.

Interviews were conducted in two rounds—one at the end of each case study—and were designed to capture 'closeout' readings on each participant. In addition, the first round of interviews roughly coincided in time with the beginning of the second case study, so some questions in that protocol served to capture a 'baseline' reading on the participants prior to the onset of their involvement in the second project. The interview format was one-on-one and followed a guided protocol created by the lead investigator. However, the interviews themselves were conducted by one of three researchers from the Stanford Center for Design Research (CDR), each an experienced interviewer: Samantha Brunhaver, Stanford Ph.D.

candidate in mechanical engineering[6]; Dr. Helen Chen, senior CDR researcher; or Dr. Sheri Sheppard, Stanford professor of mechanical engineering and CDR co-chair. The intent was to elicit candid responses from the participants by introducing a level of objectivity during the interviews that might not have been present had the lead investigator conducted the interviews. The interviews were conducted and recorded using Microsoft Lync, an online messaging and videoconferencing platform similar to Skype. The lead investigator generated transcripts from the audio-video recordings. The FEA guided interview protocols are included for reference in Appendices C and D.

Finally, throughout each case study project, the investigator maintained a log of FEA-related personal interactions with the study participants. The intent was to capture data anytime participants asked questions, initiated informal conversations, or suggested possible uses for FEA during the course of the case studies. This log eventually morphed into a set of field notes that included the investigator's reflections on the growth and evolution of the participants' understanding of FEA, how the FEA techniques and results could be more clearly communicated to them, and how their suggestions for uses of FEA could be incorporated into the scope of the product development effort.

5.4 Main and Embedded Units of Analysis

The two design projects formed the main unit of analysis for the study. Each case was defined rather broadly to include the product design, analysis, and prototype testing, as well as the product development team. Within each case, the product development team members were participants and were treated as embedded units of analysis (Yin, 2009, p. 46, 50, 53). This is a subtle but important distinction, because while the majority of the data in this research was collected at the level of individual participants, the ultimate goal of the research was to deepen understanding and draw conclusions about the effectiveness of designerly FEA in each product development effort and its impact on the teams' views.

5.5 Intervention and Communication Strategy

Both case study projects included a deliberately-structured intervention. The goal of the intervention was to implement the use of designerly FEA for vibration and shock analysis into the product development process, and to deliberately introduce FEA to the entire product development team. The steps involved with this intervention are depicted in Figure 13 in

[6] Now a faculty member at Arizona State University.

relation to the routine steps of the 'design-build-test' product development process. In each case study, the investigator utilized FEA to assess one or more design concepts prior to prototype testing. Subsequently, a physical prototype of the final design concept was fabricated and assembled into a test unit. The test results were then compared to the FEA results and the FEA model was adjusted or improved, if required, until an acceptable level agreement between FEA and test data was achieved.

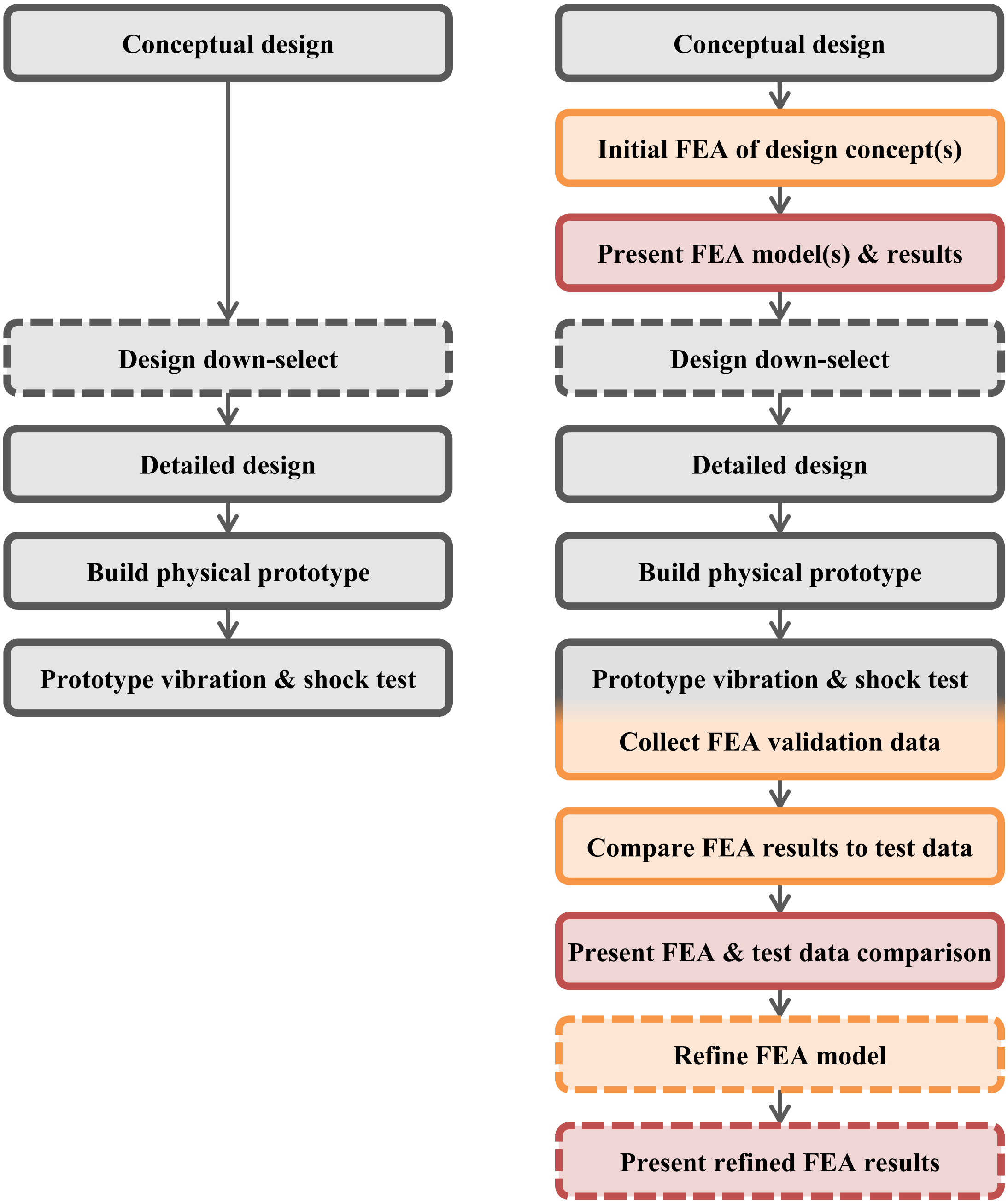
Throughout this process, information about the FEA modeling and results was provided to the product development team (i.e., the case study participants) using a combination of in-person presentations and reports distributed via email. These presentations and reports included:

- A summary of the purpose of the FEA and what design questions it was being used to answer. This also included a general discussion of the type of FEA being performed, the types of design issues it is well-suited to investigated, criteria for detecting those issues, and caveats about the types of design issues it is not well-suited to detect.
- An overview of the major assumptions in the modeling approach, such as geometry simplifications, methods used for modeling boundary conditions, rationale for selected measurement locations, estimates for material properties and damping values, and assumed linearity of the structural response.
- The numerical FEA results, which for vibration data was presented in the form of power spectral density (PSD) plots and for shock was presented in both time history plots and shock response spectrum (SRS) plots.

In addition, the presentations that were made near the end of each design project, after physical prototype testing, included:

- A comparison of the test data to the original FEA results.
- A discussion of possible causes for discrepancy between FEA results and test data.
- Results obtained using a refined FEA model (if one was created).

Chapters 6 and 7 report on the individual case studies and include a condensed version of much of this same FEA information and results that were provided to the product development teams.



(a) Routine 'design-build-test' process for ruggedized electronics

(b) Intervention structure & communication strategy

Figure 13: Elements of the intervention structure and communication strategy.
(a) Routine steps in the 'design-build-test' product development process. (b) Steps involved in implementing FEA for vibration and shock analysis are shown in orange with respect to the routine steps. Prototype testing and collection of FEA validation data are shown as a hybrid step, since a goal of designerly FEA is to perform both tasks as one activity. Red boxes denote strategic points of communication about FEA to the product development team. Dashed outlines denote steps performed on an as-needed basis.

The investigator made every effort to be as transparent as possible about how FEA was being used, what its capabilities and limitations are, the conditions under which the FEA results are trustworthy, and the conditions under which they should be viewed with a healthy skepticism. Schön (1983, p. 231) describes this as a Model II theory of action, in which the aim is to provide others with directly observable data, creating the conditions for free and informed choice. At one level, the intent of this communication strategy was to facilitate the diffusion of a well-informed and balanced view of FEA to the product development team. The idea is akin to that of a diffusion "field experiment", which Rogers defines as "an experiment conducted under realistic conditions in which preintervention and postintervention measurements are usually obtained by surveys" and in which "the intervention is some communication strategy to speed up the diffusion of an innovation" (2003, p. 128). But the ultimate goal was simply to foster dialogue, critical thinking, and understanding about FEA within the design team—and then to investigate the resulting impact in terms of the identified research questions.

5.6 Qualitative, Theory-Building Analysis Method

Eisenhardt (1989) summarizes a method for building theories from case study research that served as the basis for the present analysis. Her method essentially combines the strengths of case study research and grounded theory research (e.g., Glaser and Strauss, 1967; Corbin and Strauss, 1990). In addition to the use of theoretical sampling for case selection, replication logic, and multiple data sources, other characteristics of the method include:

- Beginning the research with a tentative idea of the research question(s) and factors that might be important, but without a theory to test.
- Specifying the population to which the results can be generalized (discussed further in Section 9.6).
- Overlap of data collection and data analysis activities, with the flexibility to make adjustments during data collection and to investigate emergent themes.
- Analysis and write-up of the individual cases (Chapters 6 and 7) followed by the use of cross-case analysis techniques (Chapter 8).
- Formation of hypotheses by generating and refining constructs, and continuous comparison of data and construct to ensure the theory fits the data (Chapter 9).

For this investigation, the analysis started during the first case study with the participants' FEA survey responses. The survey was designed to collect data on an initial litany of concepts that were deemed potentially important, based primarily on the investigator's experience in product design, product development, and use of FEA. All coding of survey data (and later of interview and field note data) was performed by the investigator.[7] This initial concept list comprised the first code, which grew and was re-shaped to focus on the most prevalent themes in the participants' responses. The concept list for the first case study project is included for reference in Appendix E. For example, participant responses confirmed that the amount of time required to utilize FEA was a factor in their thinking.

> FEA should help make design decisions, but could be costly in terms of time. … I would imagine it would be difficult for FEA to keep pace with design activities.
>
> Participant 4, beginning of case study 1

> [FEA is] most useful when kept in pace with design activities, allowing designers to see an immediate feedback at the system level.
>
> Participant 6, beginning of case study 1

The data suggested that other concepts were less active. As an example, the dollar cost of using FEA was covered in the FEA survey, but only one significant comment was received about this topic.

> The disadvantage to incorporating FEA is, like most advanced analysis, the hit to [the project] budget.
>
> Participant 1, beginning of case study 1

In yet other instances, themes emerged in the participants' responses that were not asked about directly in the survey. For example, communication about FEA results was an emerging theme, as exemplified in a variety of responses.

> One of the basic problems with engineering results is the ability to relate them to others who aren't fluent.
>
> Participant 2, beginning of case study 1

> I think just knowing something about the [FEA] model is a good start. When we get specs, for example, sometimes they come from an FEA model I know nothing about, and there doesn't seem to be a place where one could find that information.
>
> Participant 7, beginning of case study 1

> [It is important to] explain limitations of models (in units and terms relevant to engineers), explain

[7] At this point in the research, the volume of data was low, so coding and analysis was simply performed using Microsoft Excel.

> assumptions and impact they have on results, explain why you believe the model (test cases or previous cases run).
>
> Participant 9, beginning of case study 1

These survey results were used in conjunction with field notes and insights obtained from literature review to generate the first FEA interview protocol. The first round of interviews was conducted near the end of the first case study project. Nearly all the identified concepts were addressed in the first round of interviews, even those that seemed less significant in the survey responses, with the intent of 'second verification' that any particular concept was not active before removing it from the concept inventory.[8]

The coding method used for the survey data was applied once again for the interview data, with the goal of confirming the importance of identified concepts, ruling out concepts that were less prevalent, and identifying new concepts that emerged consistently in the participants' responses. For example, participant responses in the interviews confirmed that the amount of time required to utilize FEA continued to be a factor in their thinking.

> I think [FEA is] worth the time, but it's hard to get that time when you're on a fast-paced project.
>
> Participant 4, end of case study 1

> [Initially] I was a little intimidated by how long it would take to make that [FEA] model. … I think people tend to shy away from FEA just because there's an initial investment—a time investment.
>
> Participant 5, end of case study 1

On the other hand, some lines of questioning elicited less interesting responses. As an example, the participants were asked directly whether they had observed any examples of disconnects or isolation between the design process and the use of FEA. One participant made the following observation:

> I think ultimately there was some disconnect in how well we could have really used [the research investigator's] analysis right away, because we pretty much made the decision [of which design concept to select].
>
> Participant 5, end of case study 1

[8] Initial coding of the interview transcripts and data analysis was performed using Microsoft Excel, but subsequent iterations were performed using NVivo, which proved to be much better suited for viewing and analyzing the copious amounts of survey data, interview data, and field notes.

But beyond this comment, the data did not substantiate the investigator's suspicion that isolation between design and analysis activities might show up as a factor in the participants' responses.

New concepts continued to emerge from the interview data. For example, the issue of the design team members' confidence in FEA was evident.

> Initially I was just very much in my electrical engineering world, and I didn't use FEA, and so… and I just didn't have confidence in it… And so I think really, this project really changed my opinion of how critical it is to perform that analysis.
>
> Participant 5, end of case study 1

> I think this is important for FEA engineers, is that they have to be able to establish this confidence in this analysis in programs. … In my future designs, I would certainly put [FEA] under my consideration… because of the confidence that [the FEA analyst] has built for the first project.
>
> Participant 6, end of case study 1

In general, survey and interview data that pertained to more than one concept were doubled-coded. In many instances, this occurred when a participant's response to any particular question simultaneously addressed multiple concepts. In other instances, double-coding was used when a question was intended to focus on one topic, but elicited a response that touched on a different concept in a manner that suggested a 'connection' between the two in the participant's mind.

The coded survey and interview data for the first case study were assembled and viewed in a framework matrix, with the individual participants down the rows and the concept codes across the columns. Summaries were written for each cell in the matrix (i.e., for each combination of participant and code). The summarized framework matrix for the first case study is included for reference in Appendix G. This approach made it possible to inspect the data for trends in the participants' responses, iteratively grouping the identified concepts into tentative categories and generating answers to the four identified research questions.

In the second case study project, an identical analysis procedure was followed, using data from the first and second rounds of interviews (the 'baseline' and 'closeout' readings, respectively). The concept inventory for the second case study is included for reference in Appendix F, and the summarized framework matrix in Appendix H.

Corbin and Strauss (1990) describe an analysis process that becomes more abstract at each stage, moving from identifying concepts in the data, to grouping related concepts into categories, and finally building these categories into "constructs." Synthesis of the Confidence Model (Chapter 9) represented the final phase of this process. Findings from the two case studies were mapped to elements of the design process and further compared with extant literature. A combined model is proposed that incorporates the major findings from each case, offering a lens through which to view the findings while remaining grounded in the reality of the case study data.

5.7 Institutional Review Board (IRB) Approvals

The collection of survey and interview data from the case study participants was approved by both the Stanford (IRB) (protocol 24971) and the Sandia Human Studies Board (HSB) (protocol SNL1245). All members of the product development teams were aware of this ongoing research, and participants in the case studies signed a consent form required by the Sandia HSB. The research protocols, approval letters, and consent form are included for reference in Appendix I. The larger Sandia survey did not require IRB / HSB approval since the responses were anonymous.

It is worth noting that the Sandia HSB approval was particularly challenging to obtain, due to a two-fold nature of the perceived risk to participants in the study. The first was the need to ensure that the identities of participants were not associated with their responses in the interviews, so that any negative views or unflattering comments could not be used against them by Sandia management. The second was the need to ensure that appropriate precautions were taken in the interview process to protect participants from inadvertently becoming involved in any security incidents. This risk existed because some aspects of Sandia's research and development involve Official Use Only and classified information, and the interviews were conducted online by Stanford researchers who did not possess the requisite need-to-know or security clearances. Overall, it seems unlikely that a researcher outside Sandia would have been able to obtain the necessary approvals to conduct this research.

5.8 Limitations of the Research Methodology

While a significant attempt was made to heed the main points of the seminal works on case study research, this research design has limitations. Several criteria for judging the quality of case study research are discussed in this section, with an acknowledgement of limitations where they are known to exist.

5.8.1 Validity and Reliability

Yin describes four established metrics for assessing the quality of empirical social research (2009, p. 40-45). Each of these metrics is discussed below, along with the corresponding measures taken to enhance the overall quality of this research.

Construct validity. In general, construct validity requires that an investigator define what they desire to measure in terms of specific concepts, and then identify operational measures that match the concepts, preferably making use of measures from previous literature on the subject (Yin, 2009, p. 41-42). However, in theory-building case study research, the construct definition and associated measures often emerge from the analysis itself, rather than being specified a priori (Eisenhardt, 1989). In the absence of established measures for the concepts in this investigation, several other tactics were implemented that are also presented by Yin to improve construct validity. The first was the use of multiple sources of evidence, as discussed in 5.3 (2009, p. 114-118). The second was establishing a chain of evidence, which essentially entails presenting the case study data, analysis, and results in such a way that the interpretation from data to conclusions can be followed by the reader (2009, p. 122-124). Finally, the draft case study reports (Chapters 6 and 7) were submitted to all participants for review, in order to solicit feedback on the appropriateness of the conclusions drawn by the research investigator (2009, p. 182-183), a practice sometimes referred to as 'member-checking.'

Internal validity. When a case study is a vehicle for investigating how or why one event leads to another event, internal validity addresses whether the operative relationships between events have been correctly identified and described (Yin, 2009, p. 42-43). For example, an investigator could offer an interpretation of the case study data, concluding that one event led to a second event, when in fact some *third* factor may actually have actually caused the second event—representing a failure to establish internal validity. The potential for this is real in the present investigation, so several precautionary elements of the research method were implemented to mitigate this threat. First, the findings presented in the case study reports

(Chapters 6 and 7) were rooted in a fairly direct reading of the data, relying on causal relationships described by the case study participants themselves. Second, each case study included an examination of rival hypotheses for the findings, which is a technique suggested by Yin to ensure internal validity (2009, p. 43). Finally, when relationships between factors were inferred to explain the case study data (Chapter 9), they were largely tied to extant literature, which Eisenhardt (1989) recommends as a method for ensuring the internal validity of theories emerging from case study research.

External validity. This metric addresses the extent to which the findings of an investigation are generalizable beyond the immediate population being studied (Yin, 2009, p. 43). In essence, the external validity of this investigation is strengthened by examining more than one case and relying on replication logic to strengthen the findings. Generalizability across Sandia is discussed in Section 8.3, while the applicability of the investigation's results outside of Sandia is discussed in more detail in Section 9.6.

Reliability. The objective of reliable findings is to ensure that if another investigator followed the same procedure and repeated the same case study over again, they would arrive at the same findings and conclusions (Yin, 2009, p. 45). Two recommended techniques for enhancing reliability were applied in this investigation. First, the process of collecting, coding, analyzing, and interpreting data was made as operational as possible, with the survey protocol, interview protocols, coding schemes, and analysis methods presented in the body and appendices of this document (Yin, 2009, p. 45). Second, while the publication of a full, digital 'case study database' (Yin, 2009, p. 118-122) was not covered by the IRB approvals, much of the coded interview data are presented for inspection in the appendices.

5.8.2 Researcher Bias

This research was conducted by one investigator, with the notable exception that a team of experienced interviewers conducted the interviews per the guided interview protocols. In general, the use of multiple investigators is preferred, as it tends to strengthen the findings and generate more divergent perspectives of the data (Eisenhardt, 1989).

The method of participant-observation introduces the potential for biases (Yin, 2009, p. 112-113), which certainly exists in this research. The investigator approached this research with the idea that a designerly use of FEA could benefit the case study product development efforts, as discussed in Section 4.3, and was significantly involved in various capacities in the product development efforts for both cases. The intent of this research design was to demonstrate the use of FEA to the design teams, collect data on how these encounters with FEA impacted the views of the participants, and then perform a theory-building analysis to synthesize the main findings into a description of how the design teams perceive FEA. This approach required the investigator to pivot between roles as design team member, advocate for FEA, observer/listener, and social scientist. Clearly, this is not a conventional research approach, and could be fairly criticized as such. The intent of the investigator was to use a sufficiently methodical approach so as to ensure an acceptable level of reliability in the findings.

In particular, this approach appears to contrast strongly with assertions by Yin, who plainly states that case study research should not be used to advocate particular issues (2009, p. 72). To be clear, the investigator supports a designerly approach to using FEA for product development, but addressed the question of the *participants'* perceptions of FEA with only loosely-held ideas and a flexible view of incoming data—a requirement of unbiased case study research.

6 Case Study 1: Modification of an Existing Design

> Much everyday design work entails the use of precedents or previous exemplars—not because of laziness by the designer but because the exemplars actually contain knowledge of what the product should be.
>
> Cross (2007, p. 126)

This chapter covers the first case study design project. Section 6.1 provides an overview of the design requirements and the participants in the case study, who were members of the product development team. Section 6.2 covers technical details of the design effort, including design concepts, FEA modeling approach and assumptions, physical prototype testing, and comparison of FEA results to the test data. Section 6.3 presents the main findings from the survey, interview, and field note data. Section 6.4 concludes with an overall discussion of the case study and findings.

6.1 Overview

This case study design project involved a team at Sandia National Laboratories that was tasked with modifying an existing electronics design. This section provides an overview of the project. Section 6.1.1 outlines the design task. Section 6.1.2 summarizes the makeup of the product development team and compares it to the Sandia product development community overall, using the Context Assessment data (Chapter 3). Section 6.1.3 presents the project timeline.

6.1.1 Design Requirements

The design task consisted of incorporating a small electronics module into a larger electronics assembly. These two products were already in existence and are shown for reference in Figure 14. Due to external space limitations, the new, 'modified' electronics assembly with the incorporated electronics module was required to fit almost entirely within the volume of the original electronics assembly. The weight of the modified electronics assembly was also required to be very similar to that of the original design. Finally, the size and position of several electrical connectors mounted to the external housing, visible in Figure 14(a), were required to remain unchanged.

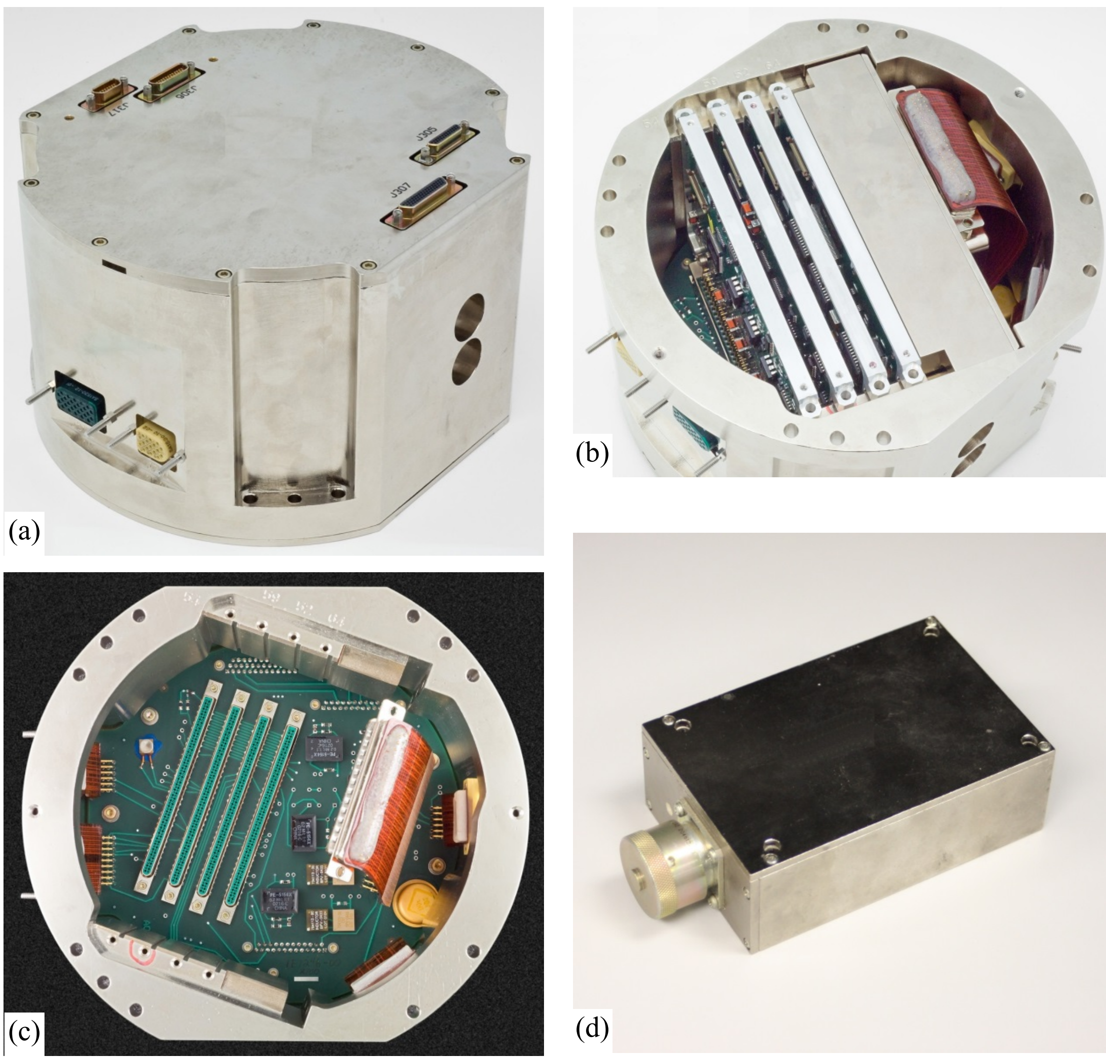


Figure 14: Existing products, to be incorporated into a new combined design.
(a) External view of original electronics assembly. (b) View with cover removed. (c) View with cover and plug-in cards removed. (d) Separate electronics module to be incorporated into the larger electronics assembly.

Both the original electronics assembly and the smaller electronics module had their own vibration and shock specifications, which they had been shown via prior testing to meet. These require the electronics to function without performance degradation during and after application of the specified vibration and shock environments. The modified design, with the electronics module incorporated, was required to meet the vibration and shock specifications of the original electronics assembly. As a result of this, two 'goals' were identified for the modified design:

- Minimize the vibration and shock levels to which the circuit boards are subjected, and/or maintain as much mechanical design similarity to the original electronics assembly as possible; and
- Ensure that the electronics module was not subjected to higher vibration and shock levels than those to which it had previously been tested.

The idea was that meeting these two goals would maximize the likelihood that the modified electronics assembly, including the incorporated electronics module, could successfully pass vibration and shock testing. Finite element analysis was used during the design process to assess the design concepts in this regard, as described in Section 6.2.

6.1.2 Product Development Team

The profiles of the case study product development team members are shown in Table 20 in terms of their technical backgrounds, length of time at Sandia, and present role(s) at Sandia. Table 21 compares these team demographics to the Sandia product development community overall, using data from the Sandia Context Assessment (Chapter 3). Similarly, Table 22 summarizes the team's previous exposure to FEA and compares it to the Sandia CAS data. As these tables show, the product development team was reasonably representative of the larger Sandia population in terms of these metrics over the two-year period of the investigation. As previously mentioned, it should also be emphasized that the investigator was already experienced in the area of packaging design for ruggedized electronics, and was *not* simply an FEA analyst 'brought in' to implement the use of FEA for this case study.

Table 20: Profiles of Case Study 1 product development team members.

Part. no.	Technical background	Time at Sandia	Self-described role(s)
1	Electrical eng.	≥ 26 years	Project / team leader
2	Electrical eng.	≥ 26 years	Electrical eng., Manuf. eng., Project / team leader
4	Electrical eng.	6 – 10 years	Electrical eng., Project / team leader
5	Electrical eng.	6 – 10 years	Project / team leader
6	Electrical eng.	≤ 5 years	Electrical eng.
7	Mechanical eng.	≤ 5 years	Mechanical eng.
8	Business admin., Aerospace eng.	≤ 5 years	Program mgmt., Systems eng.
9	Mechanical eng.	21 – 25 years	Dept. manager
11	Electrical eng.	11 – 15 years	Dept. manager
Investigator	Mechanical eng.	6 – 10 years	Mechanical eng., FEA analyst

Table 21: Demographics of Case Study 1 participants compared to Sandia overall.
The team was reasonably representative of Sandia overall in terms of these demographic data.

Survey Question	CAS-pre		Case 1		CAS-post	
	No.	%	No.	%	No.	%
What is your technical background or degree field? (Select all that apply.)						
Electrical engineering	32	47.8	6	60.0	25	45.5
Mechanical engineering	26	38.8	3	30.0	23	41.8
Other	15	22.4	1	10.0	10	18.2
How long have you worked at Sandia (or your current employer)?						
≤ 5 years	16	23.9	3	30.0	18	32.7
6 - 10 years	13	19.4	3	30.0	8	14.5
11 - 15 years	11	16.4	1	10.0	9	16.4
16 - 25 years	8	11.9	1	10.0	10	18.2
≥ 26 years	19	28.4	2	20.0	10	18.2
Total	67	100.0	10	100.0	55	100.0
What is your present role at Sandia? (Select all that apply.)						
Department manager	6	9.0	2	20.0	8	14.5
Electrical engineer	17	25.4	3	30.0	16	29.1
Mechanical engineer	19	28.4	2	20.0	16	29.1
Project lead	16	23.9	4	40.0	18	32.7
Systems engineer	20	29.9	1	10.0	15	27.3
Other	13	19.4	2	20.0	8	14.5

Table 22: FEA exposure of Case Study 1 participants compared to Sandia overall.
The team was reasonably representative of Sandia overall in terms of their familiarity with FEA.

Survey Question	CAS-pre		Case 1		CAS-post	
	No.	%	No.	%	No.	%
Have you ever seen FEA used on your past projects?						
Yes	58	86.6	8	80.0	51	92.7
No	9	13.4	2	20.0	4	7.3
Total	67	100.0	10	100.0	55	100.0
Have you ever used FEA software?						
Yes	26	38.8	3	30.0	29	52.7
No	41	61.2	7	70.0	26	47.3
Total	67	100.0	10	100.0	55	100.0
Have you ever taken a course on FEA?						
Yes	21	31.3	3	30.0	22	40.0
No	46	68.7	7	70.0	33	60.0
Total	67	100.0	10	100.0	55	100.0

6.1.3 Project Timeline

The entire project was operated under a relatively tight schedule, with approximately nine months devoted to concept generation, evaluation, and down-selection; detailed mechanical and electrical design; circuit board and mechanical hardware procurement; assembly of a fully-functional prototype; and vibration and shock testing. The case study timeline, with critical project steps and survey/interview data collection points, is shown in Figure 15.

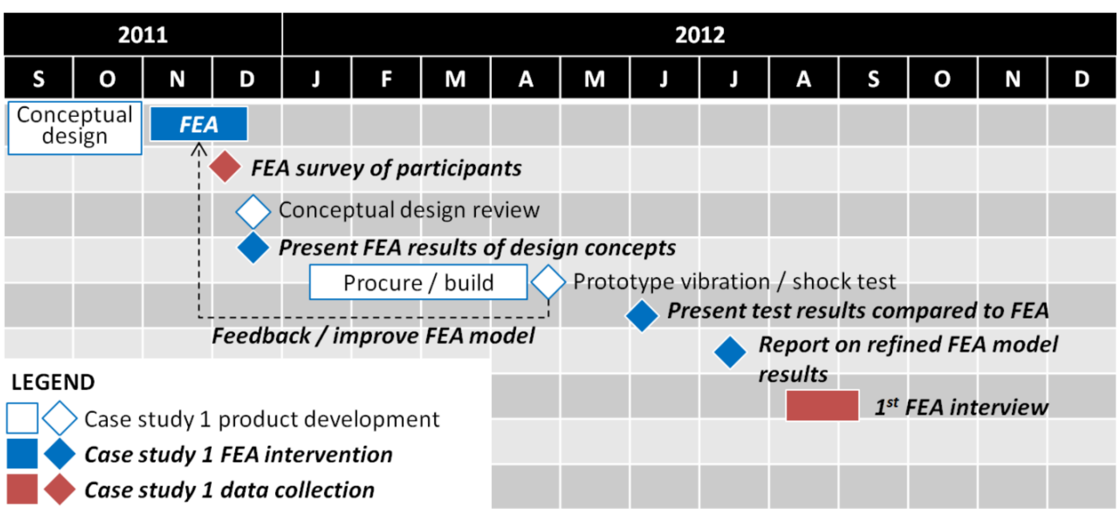
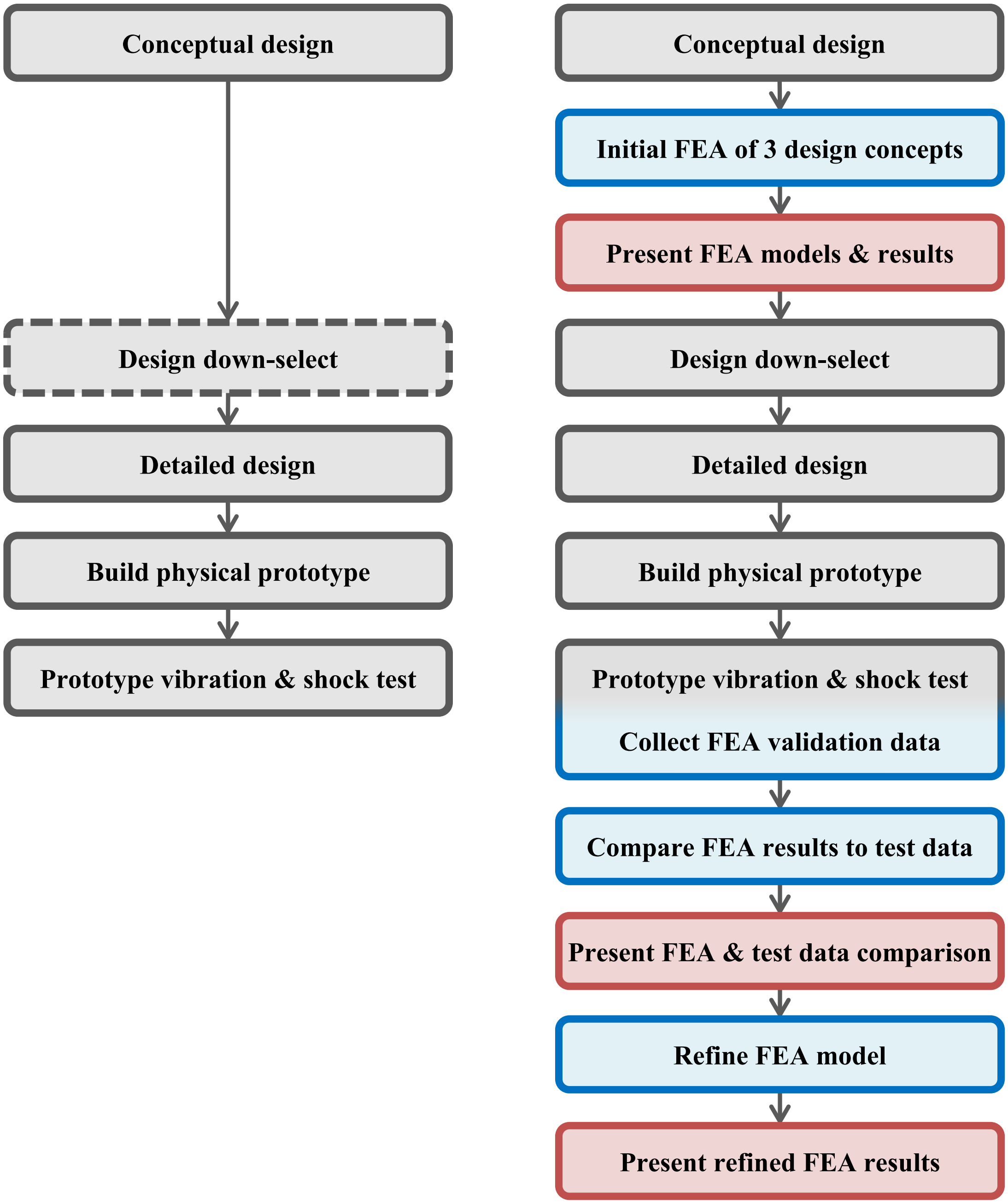


Figure 15: Case study 1 timeline.
Critical project steps and survey/interview data collection points are shown.

6.2 Design, FEA, and Prototype Testing

This section summarizes the design concepts and important aspects of the FEA modeling and physical prototype testing that were performed as part of the product development effort. Elements of the intervention strategy are depicted in Figure 16 in contrast with the routine elements of the 'design-build-test' product development approach.

Section 6.2.1 presents three design concepts that were generated. Section 6.2.2 provides an overview of the FEA model for each design concept, and Section 6.2.3 presents the initial results of the FEA modeling. Section 6.2.4 describes the overall rationale and the role of the FEA modeling in the selection of one concept to carry forward for prototype testing, which is summarized in Section 6.2.5. Finally, the experimental results are compared to the original FEA results in Section 6.2.6, along with areas that were identified for improving the FEA model.



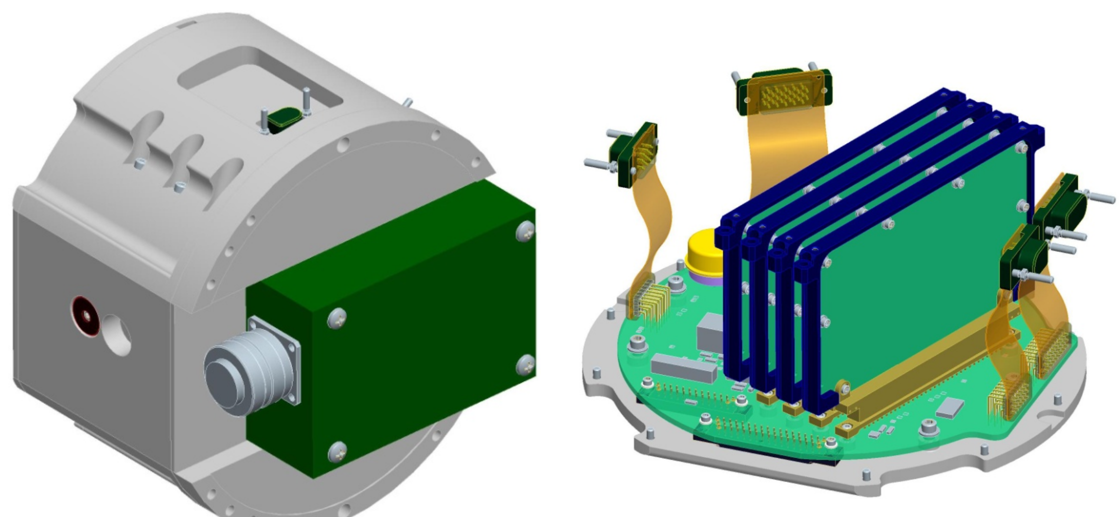
(a) Routine 'design-build-test' process for ruggedized electronics

(b) Case study 1 intervention structure & communication strategy

Figure 16: Case study 1 intervention structure and communication strategy.
(a) Routine steps in the 'design-build-test' product development process. Dashed outlines denote steps performed on an as-needed basis. (b) Steps involved in implementing FEA for vibration and shock analysis in case study 1 are shown in blue with respect to the routine steps. Red boxes denote strategic points of communication about FEA to the product development team.

6.2.1 Design Concepts

Three design concepts were developed for incorporating the electronics module into the original electronics assembly. In the first concept, shown in Figure 17, the overall length of the electronics assembly was reduced by about 0.5 inches, and the electronics module was mounted on a redesigned end cover. To accommodate this, the heights of the plug-in circuit board cards were likewise reduced in height by about 0.5 inches. Due to the strong design similarity to the original electronics assembly, this concept was highly favored by the design team and was considered the 'baseline' design concept.



(a) (b)

Figure 17: Concept 1 electronics assembly with attached electronics module.
The electronics assembly was shortened with the electronics module mounted to the end cover. (a) External view. (b) Internal view, with main housing, one end cover, and the electronics module removed.

The second concept, shown in Figure 18, was identical to concept 1, with the exception that a different electrical connector was used for the plug-in cards. This electrical connector was available for purchase with a substantially shorter lead time (2 weeks vs. 12 weeks for the connector used in concept 1), but it forced a reduction in circuit board thickness from 0.094 inches to 0.062 inches. In general, for this class of products, thinner circuit boards tend to experience higher peak acceleration levels and are therefore not as rugged in vibration and shock environments, so this change of connector style introduced an undesirable risk.

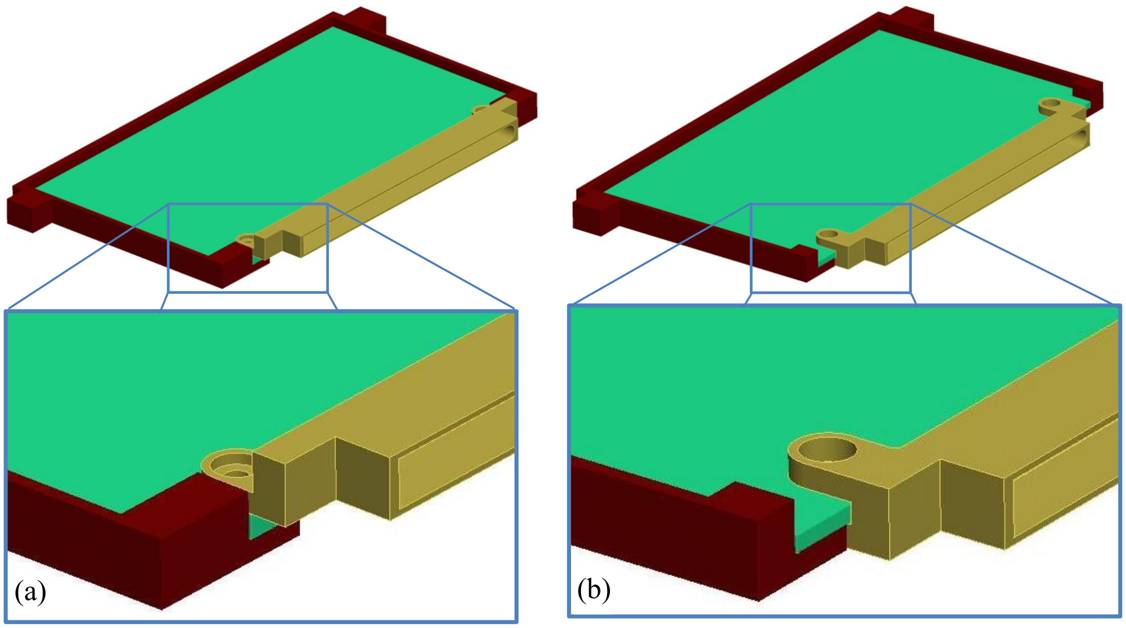
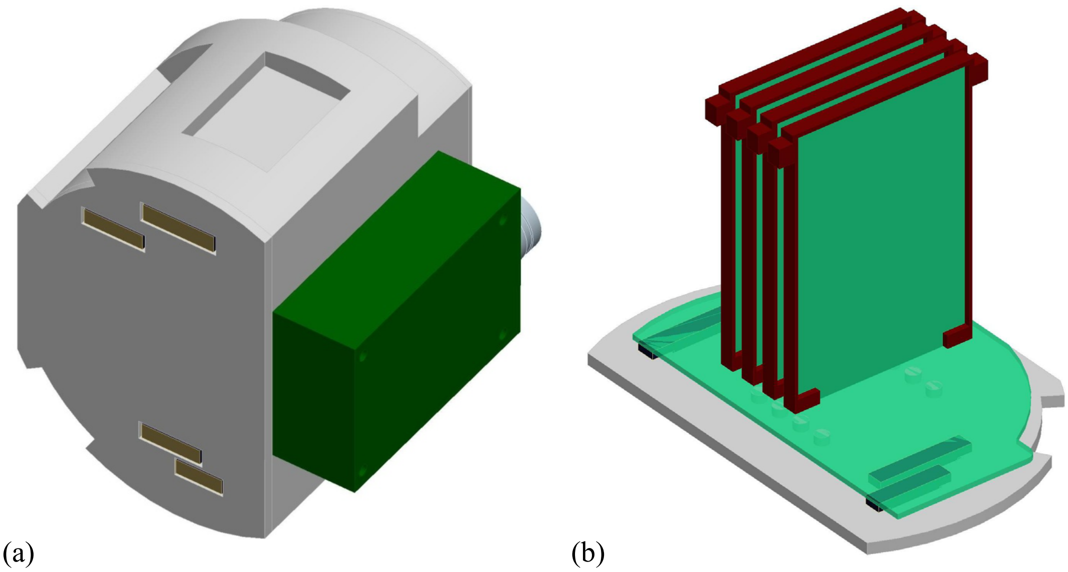


Figure 18: Concept 2 plug-in card electrical connector compared to Concept 1.
Other aspects of Concept 2 were identical to Concept 1. (a) Concept 1, with offset connector style and plug-in card thickness of 0.094 inches. (b) Concept 2, with in-line connector style and plug-in card thickness of 0.062 inches.

The third concept, shown in Figure 19, was an altogether different concept in which the electronics assembly housing was redesigned to include a flat side for mounting the electronics module. This required a more substantial change than Concept 1 to not only the main housing geometry, but also the two end covers, the motherboard, and the plug-in cards. Due to the reduction in the width of the plug-in cards, it would also require an altogether different type of electrical connector between the motherboard and the plug-in cards. As such, Concept 3 was perceived by the design team as a more uncertain, less well-understood design. On the other hand, as a substantially different concept, it also offered the possibility of reducing the acceleration levels seen at the plug-in cards, the motherboard, and/or the electronics module.



(a) (b)

Figure 19: Concept 3 electronics assembly with attached electronics module.
The main housing of the electronics assembly was redesigned, with the electronics module mounted to the side. (a) External view. (b) Internal view, with main housing, one end cover, and the electronics module removed.

6.2.2 FEA Models and Assumptions

Finite element analysis was used to predict the structural response of each design concept to the specified vibration and shock requirements. Specifically, the intent was to compare the vibration and shock levels reached at both the circuit boards and the electronics module, in order to determine which design concept, if any, held an advantage in terms of the two design goals identified in Section 6.1.1. The design models were developed using Pro/Engineer Wildfire 4, which is heavily utilized at Sandia for much of its design and product development. The FEA was conducted using Mechanica, the integrated FEA software available with Pro/Engineer.[9]

Generating the FEA models to conduct this comparison involved a variety of simplifications and assumptions, each of which is influenced by the specific purpose of the FEA models. Each presentation to the product development team of the FEA results (in December 2011 and again in June 2012) began with a brief reminder of these assumptions and limitations, which are summarized below. Detailed information on the FEA model construction and the various assumptions involved is compiled in Appendix K.

[9] Pro/Engineer Wildfire is now Creo Parametric, and Mechanica is now Creo Simulate. Both are made by Parametric Technology Corporation.

Geometry. The goal with these models was to include sufficient detail to accurately model the *displacements* and *accelerations* of the parts in response to vibration and shock loading—but no more detail than necessary, in order to limit the amount of time needed for the models to run. This involved the removal of a variety of small, unnecessary features from the Pro/Engineer design models shown in Figure 17 through Figure 19 such as fillet radii, notches, holes, electrical components on the circuit boards, various mechanical fasteners and hardware, etc. This point is especially important, because mechanical FEA models are very often used to calculate *stress*, which requires more accurate geometric representation in the vicinity of the high stresses than is required to model displacements and accelerations. External views of the resulting meshes are shown in Figure 20.

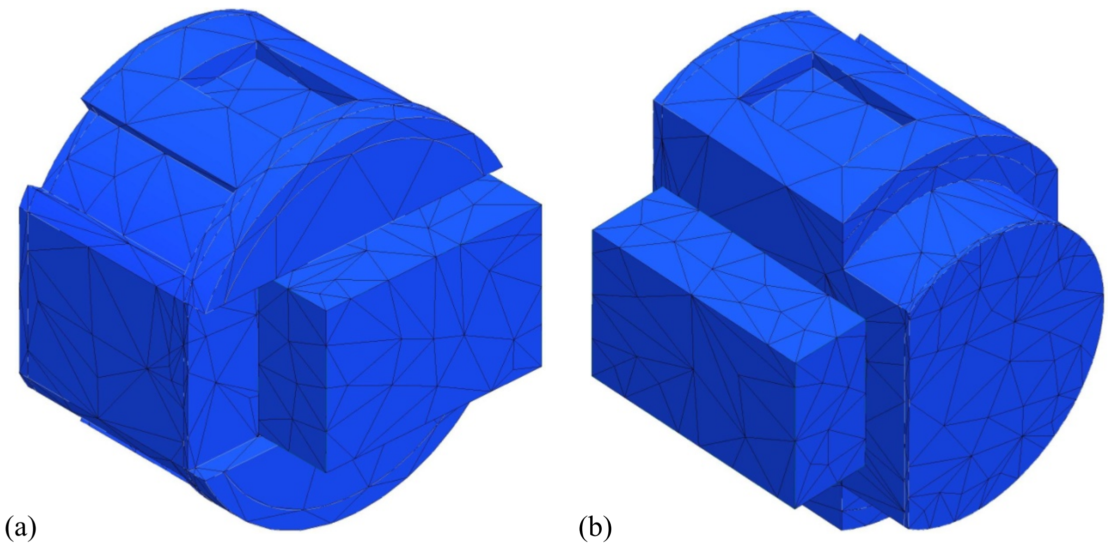


Figure 20: P-element meshes used for vibration and shock analyses.
(a) Concept 1 mesh. (b) Concept 3 mesh.

Element types. The FEA models were built using p-elements, with the circuit boards modeled using shell elements with bending (i.e., plates), the plug-in card electrical connectors modeled using beam elements, and the remaining 'bulky' parts modeled using tetrahedral elements.

Boundary conditions and loading. The models were constrained by 'fixing' all six degrees of freedom of the entire surface of the mounting flange that mates with the next-assembly. The vibration and shock loads were applied as specified accelerations.

Connections. The models used a 'bonded' connection between the main housing and each end cover, and links for the mechanical connection formed by the electrical connectors between the plug-in cards and the motherboard. For all other part-to-part connections, bolted joints were simply modeled as a locally bonded region between each part.

Material properties. Linear-elastic material models were used for all components in the design. Linear-elastic is the simplest type of material model, requiring values for only Young's modulus and Poisson's ratio. For dynamic FEA models, the material density is also required. The linear-elastic approximation is somewhat crude for the circuit boards and other non-metallic items in the design. It is a better approximation for the metal parts, such as the main housings, end covers, and plug-in card frames.

Measurement points. A variety of locations were selected for measuring the acceleration response of the designs, several of which are shown in Figure 21. The intent of measuring accelerations was two-fold: (1) to use the responses at these locations for comparing and evaluating the three design concepts; and (2) later, during physical prototype testing of the selected concept, to place accelerometers at these locations to collect data for validating/improving the FEA model. In a subsequent version of the FEA model for concept 1, the point at the base of the electronics module (SMB) was added.

Damping. An initial damping value of 3% was used, based on limited historical data for similar, unpotted electronics assemblies.

Non-linearities. These FEA models are of a class often referred to as "structural dynamics" or "linear dynamics"—i.e., they model the linear-elastic response of the structures to various types of dynamic loading and do not include non-linear effects. The implicit assumption was that the dynamic behavior of these electronics assemblies could be described reasonably well using linear structural dynamics.

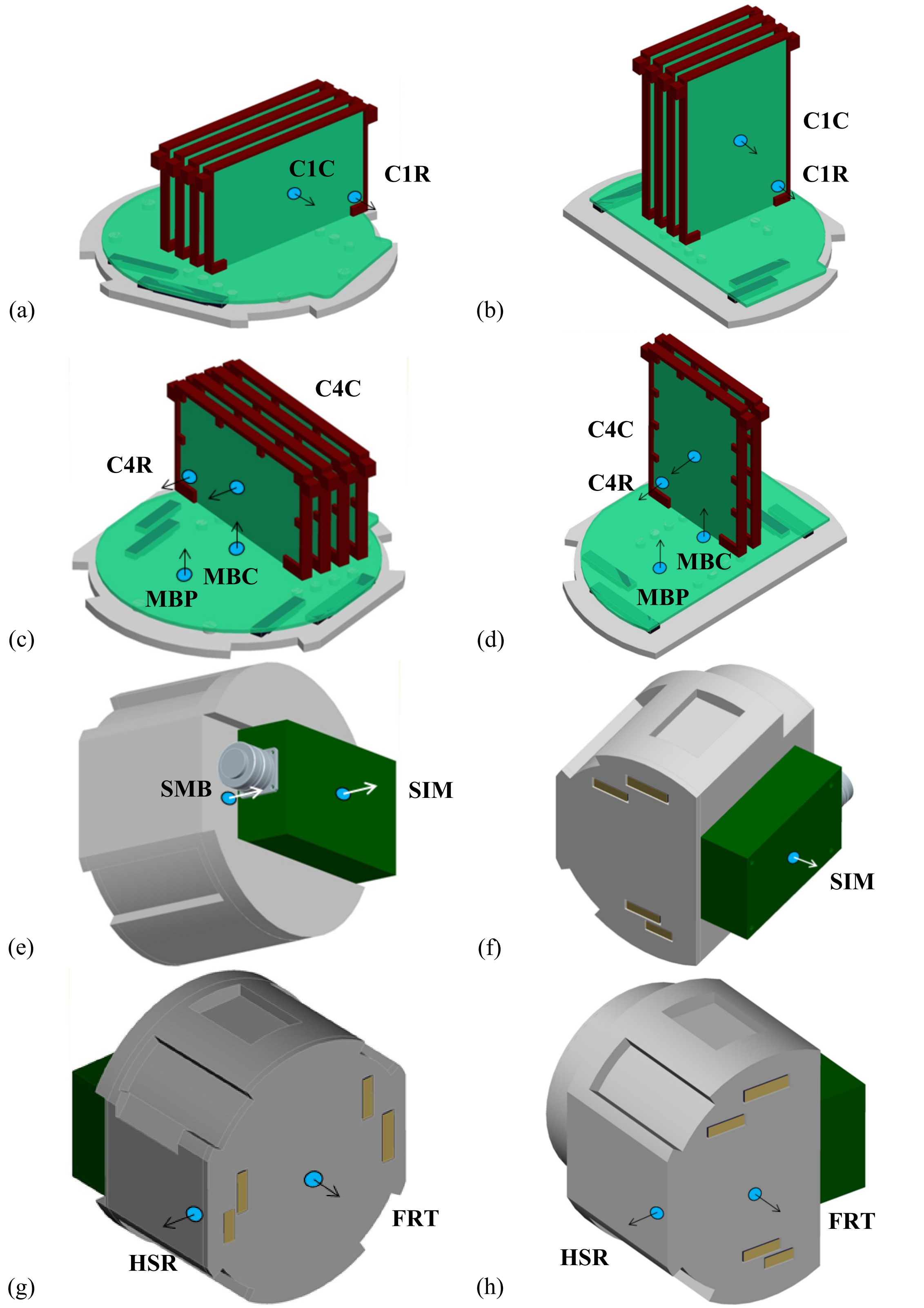


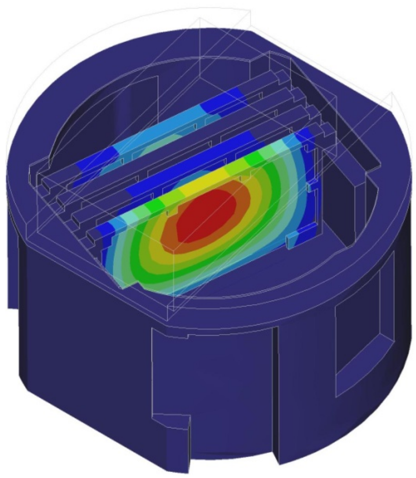
Figure 21: Response measurement locations.
Concepts 1 and 2 are shown on the left. Concept 3 is shown on the right. (a)-(b) First plug-in card. (c)-(d) Motherboard and fourth plug-in card. (e)-(f) Electronics module. (g)-(h) Front cover and side of housing.

6.2.3 FEA Results

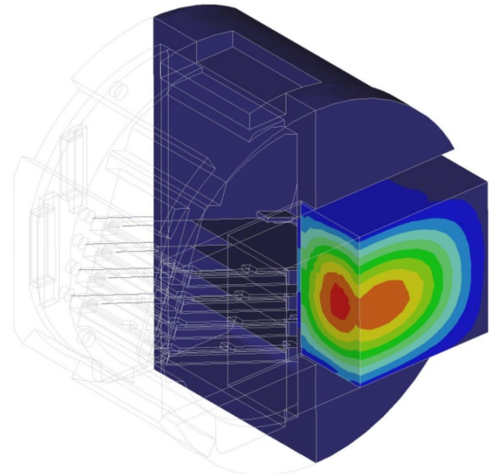
The FEA results for the three design concepts were compared to see if any concept held a distinct advantage in terms of its response in vibration and shock environments. The results presented in this section are based on a presentation given in person by the research investigator to the product development team in December 2011. The response of the plug-in cards and the electronics module were identified as the most important results, since severe resonances at these locations would introduce a high risk of damaging the electronics.

Mode shapes and natural frequencies. Figure 22 shows a comparison of the mode shapes and associated natural frequencies for the plug-in cards and electronics module. In the most general terms, higher first natural frequencies result in smaller displacements during vibration and shock environments, thereby reducing strain and stress levels and minimizing the associated fatigue damage incurred by solder joints, fasteners, and other potential failure points in a design. Of all three designs, concept 1 has the highest first natural frequency for the plug-in cards. Concept 2 has a slightly lower first natural frequency at the plug-in cards due to the thinner circuit boards. Concept 3 has a substantially lower first natural frequency at the plug-in cards due to the design's altogether different form factor. At the electronics module, concepts 1 and 2 have similar first natural frequencies, whereas the first natural frequency of concept 3 is somewhat lower.

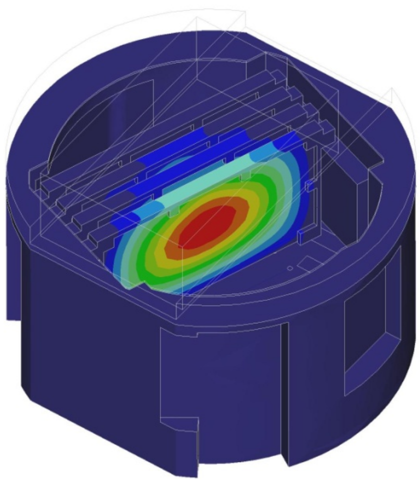
Plug-in card response in random vibration. Figure 23 shows a comparison of the random vibration response for each concept at the plug-in cards. The design goal was to minimize amplification of the vibration environment, but a strong resonance is visible in each response due to each concept having the first natural frequency of the plug-in cards right in the range of maximum input (approximately 450-650 Hz). Concept 1 had the highest first natural frequency, followed by concept 2, which used thinner circuit boards, and concept 3, which used a larger aspect ratio for the plug-in card geometry. In terms of G-rms (root-mean-square acceleration level, which is a very rough indicator of the overall severity of a random vibration environment), concepts 1 and 3 are roughly equivalent, but concept 2 is somewhat higher.



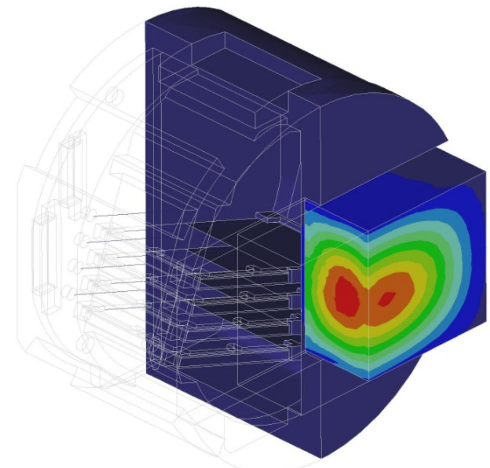
(a) Concept 1, plug-in cards, 670 Hz



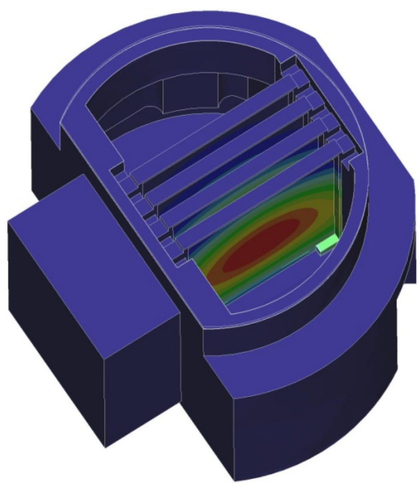
(b) Concept 1, electronics module, 1588 Hz



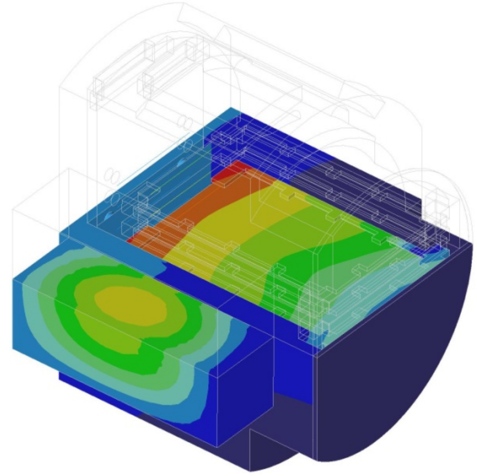
(c) Concept 2, plug-in cards, 620 Hz



(d) Concept 2, electronics module, 1533 Hz



(e) Concept 3, plug-in cards, 460 Hz



(f) Concept 3, electronics module, 1326 Hz

Figure 22: Important mode shapes and associated natural frequencies.
(a)-(b) Concept 1. (c)-(d) Concept 2. (e)-(f) Concept 3. The design goal was to increase the natural frequencies associated with these important mode shapes.

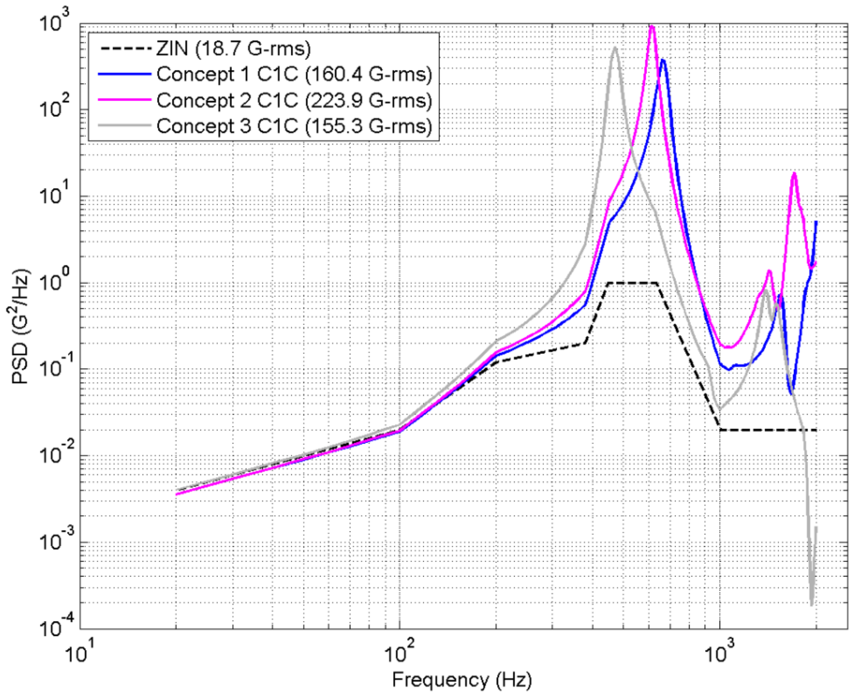


Figure 23: Random vibration response at center of plug-in cards.
The design goal was to minimize amplification of the vibration environment, but a strong resonance is visible in each response due to each concept having the first natural frequency of the plug-in cards right in the range of maximum input (approx. 450-650 Hz). In terms of overall G-rms level, concepts 1 and 3 are roughly equivalent, but concept 2 is somewhat higher.

Motherboard response in random vibration. Figure 24 and Figure 25 show comparisons of the random vibration response for each concept at two locations on the motherboard: the center, and another point in an unsupported span of the motherboard located midway between the center and edge. The design goal was to minimize amplification of the vibration environment, and concept 3 faired best in this regard, presumably due to the smaller size of the housing end cover to which the motherboard is mounted. Additionally, in concepts 1 and 2, the four plug-in cards were placed off-center of the motherboard, resulting in a larger unsupported span than was present in concept 3. Concepts 1 and 2 were identical except for the lower first natural frequency of the concept 2 plug-in cards, an effect which apparently coupled into the response of its motherboard, as evidenced by the slightly reduced frequency at which the main resonance in the motherboard occurs. Despite all this, the motherboard geometry in concepts 1 and 2 was identical to that of the existing electronics assembly, which was already known to be sufficiently rugged.

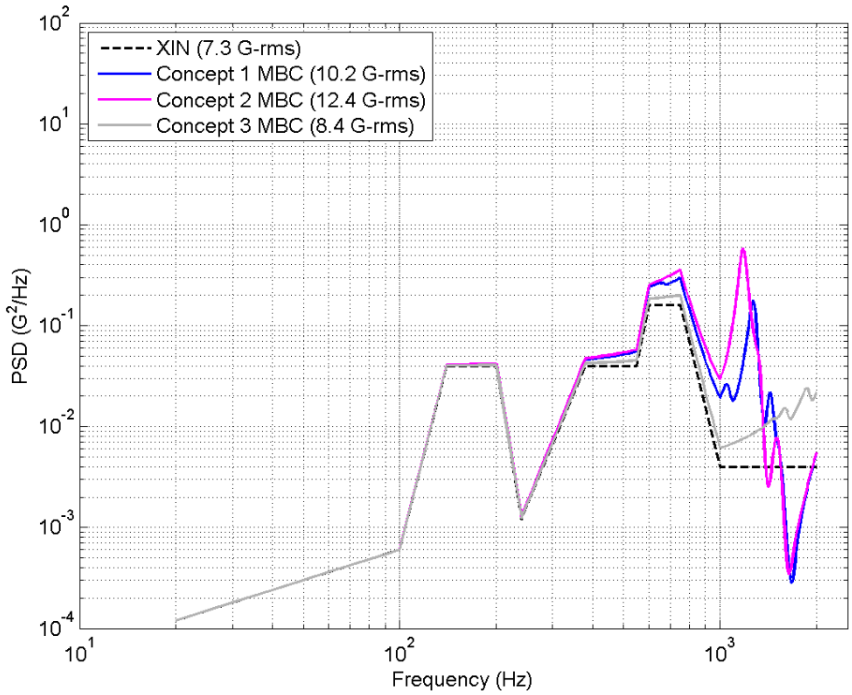


Figure 24: Random vibration response at center of motherboard.
The design goal was to minimize amplification of the vibration environment, and concept 3 faired best in this regard. However, the motherboard geometry in concepts 1 and 2 was already known to be sufficiently rugged.

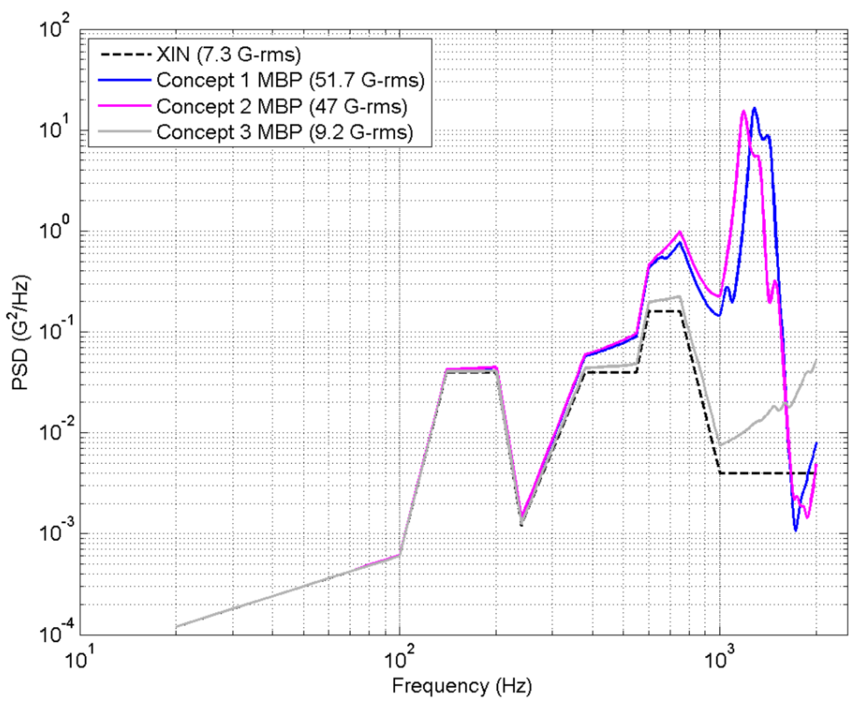


Figure 25: Random vibration response at a second point on the motherboard.
The lower first natural frequency of the plug-in cards for concept 2 couples into the motherboard response, shifting it slightly lower relative to that of concept 1.

Response at electronics module in random vibration. Figure 26 shows a comparison of the random vibration response for each concept at the electronics module. The design goal was to prevent the electronics module from being subjected to vibration levels in excess of those to which it had already successfully been tested, which are shown as a dashed red line in Figure 26. Concepts 1 and 2 came very close to achieving this goal, but concept 3 did not, due primarily to the different orientation of the electronics module in this concept, and the fact that the main electronics assembly has different vibration specifications in the different directions. The FEA results thus suggested that concept 3 presented a higher risk of subjecting the electronics module to vibration levels that it would not be able to survive.[10]

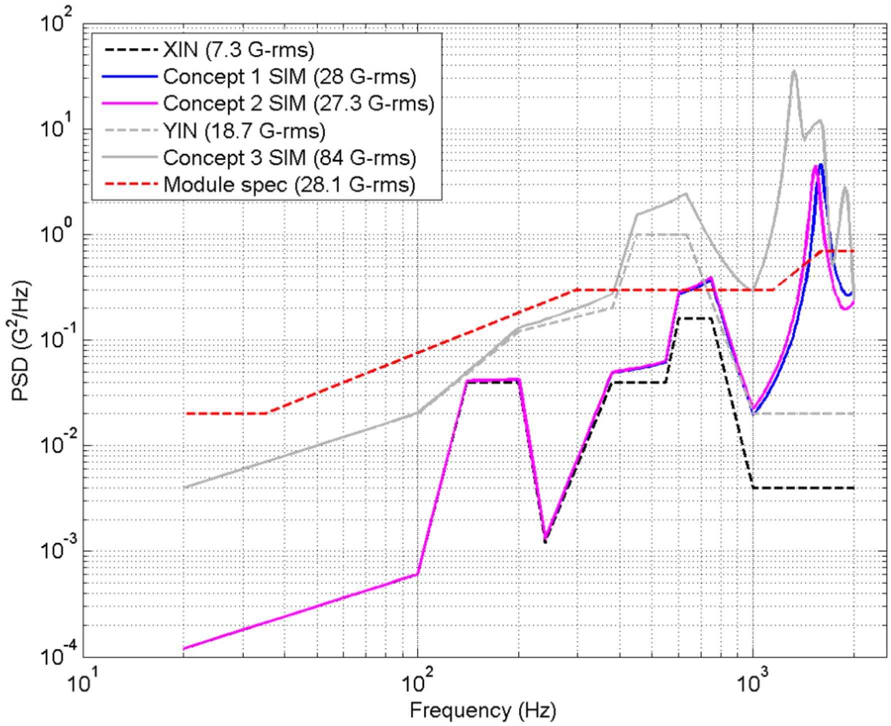


Figure 26: Random vibration response at electronics module.
The design goal was to prevent the electronics module from being subjected to vibration levels in excess of those to which it had already successfully been tested, which are shown as a dashed red line. Concept 3 did not come close to achieving this goal, due primarily to the different orientation of the electronics module in this concept, and the fact that the main electronics assembly has different vibration specifications in the different directions (dashed black and dashed gray lines).

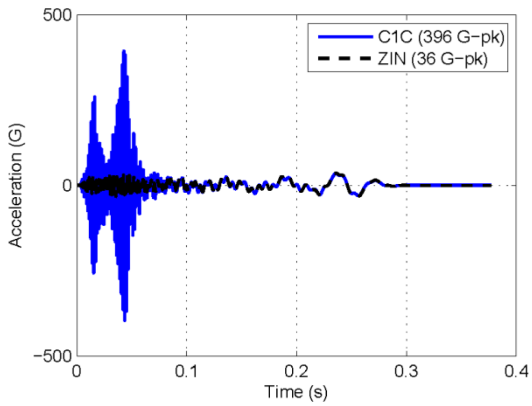
[10] These initial FEA models measured the response on the top of the electronics module, which therefore includes its own deformation in the measured response. A better location used in subsequent version of the FEA models is on the cover plate to which the electronics module is attached, adjacent to the base of the module.

Plug-in card response in shock. Figure 27 shows a comparison of the time-history response at the center of the plug-in cards for low-frequency and high-frequency shock inputs. The design goal was to minimize the peak acceleration levels at the center of the plug-in cards. All three concepts exhibit a strong resonance for both types of shock, but the peak acceleration levels for concepts 1 and 2 are substantially higher than those for concept 3.

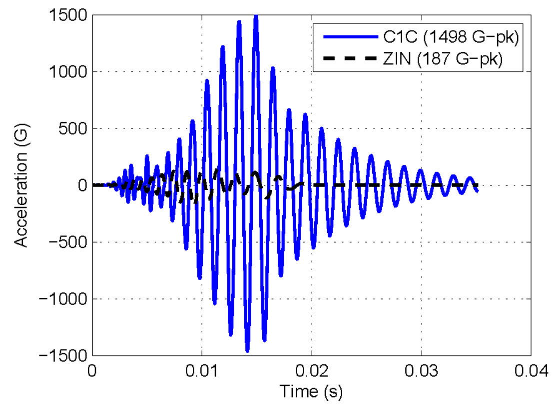
Response at electronics module in shock. Figure 28 shows a comparison of the calculated shock response spectrum (SRS) for each concept at the electronics module, for both low-frequency and high-frequency shock inputs. The SRS is a commonly-used reduction algorithm that enables a direct comparison of otherwise dissimilar shock profiles, in order to assess their relative severity (Kelly and Richman, 1969; Himelblau et al., 1994; Rubin, 1996; Goyal et al., 2000; Martin et al., 2010). The electronics module had been shown via previous testing to survive two different shocks, which were available in the product documentation in SRS form. These SRS profiles are shown in Figure 28 as solid and dashed red lines. The design goal was to prevent the electronics module from being subjected to shock levels in excess of its previously-tested levels, with the comparison performed in the SRS domain. Concepts 1 and 2 roughly met this goal for both the low-frequency and high-frequency shock inputs. Concept 3 met the goal for the low-frequency shock input, but failed for high-frequency shock. The FEA results thus suggested that concept 3 presented a higher risk of subjecting the electronics module to shock levels that it would not be able to survive.

Time required to build and run FEA models. These initial FEA models of the three design concepts took about 1-1/2 months at 1/2 full-time-equivalency (i.e., the equivalent of about three calendar weeks full-time) to develop, de-bug, run, and pull together all the results. Adapting the concept 1 FEA model into a model for concept 2 required minimal time due to their strong similarity. Once the models were successfully setup and debugged, running a modal analysis required about 2 CPU hours per concept. Running three vibration profiles in each of three directions required an average of about 26 CPU hours per concept. Similarly, running three shock profiles in each of three directions required about 13 CPU hours per concept. In total, 123 CPU hours were required to run all simulations for all three concepts.[11]

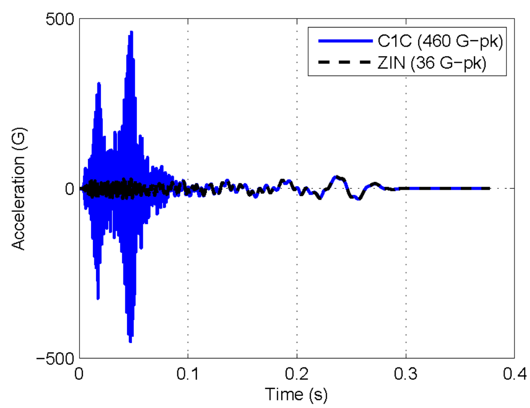
[11] Mechanica does the majority of its calculations without taking advantage of multiple processors. For modal and random vibration analysis, total CPU time was typically about 10 to 20 percent more than total elapsed time. For time-history shock analysis, CPU and total elapsed time were essentially identical.



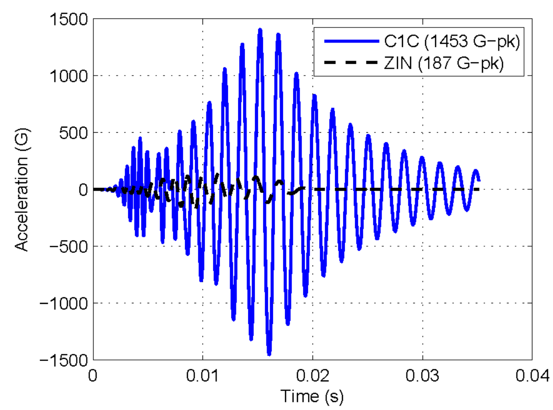
(a) Concept 1, low-frequency shock



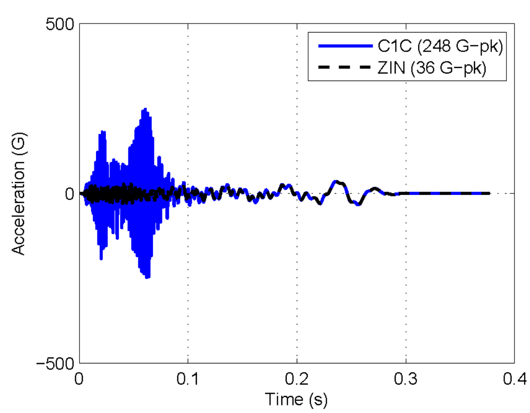
(b) Concept 1, high-frequency shock



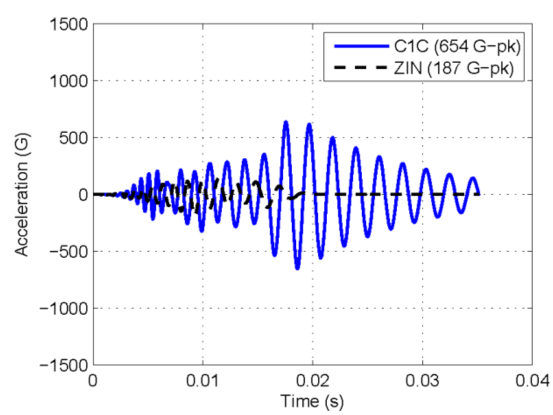
(c) Concept 2, low-frequency shock



(d) Concept 2, high-frequency shock

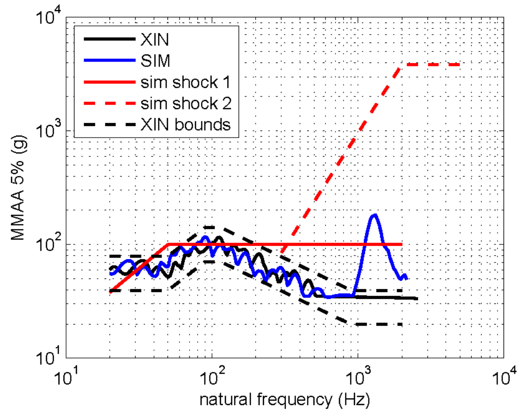


(e) Concept 3, low-frequency shock

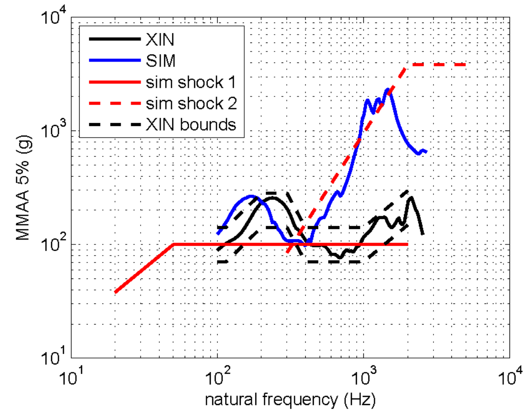


(f) Concept 3, high-frequency shock

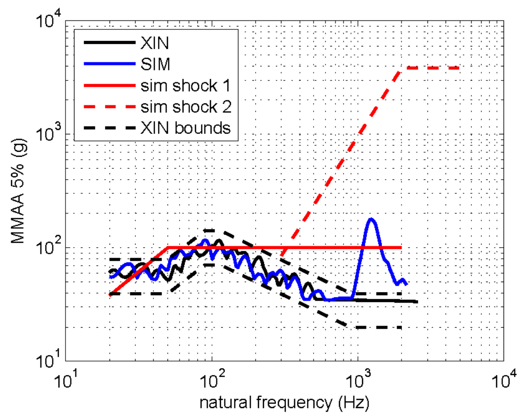
Figure 27: Time-history response at center of plug-in cards for shock inputs.
(a)-(b) Concept 1. (c)-(d) Concept 2. (e)-(f) Concept 3. The design goal was to minimize the peak acceleration levels at the center of the plug-in cards. All three concepts exhibit a strong resonance for both types of shock. The peak acceleration levels for concepts 1 and 2 are higher than those for concept 3.



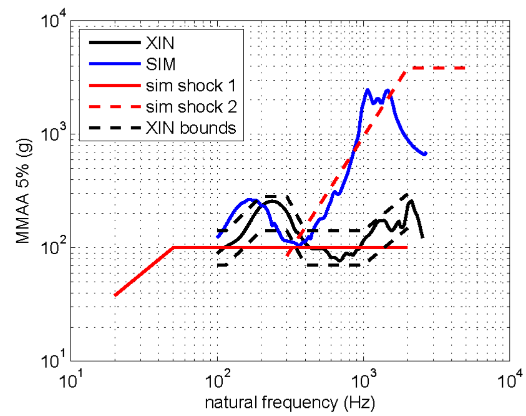
(a) Concept 1, low-frequency shock



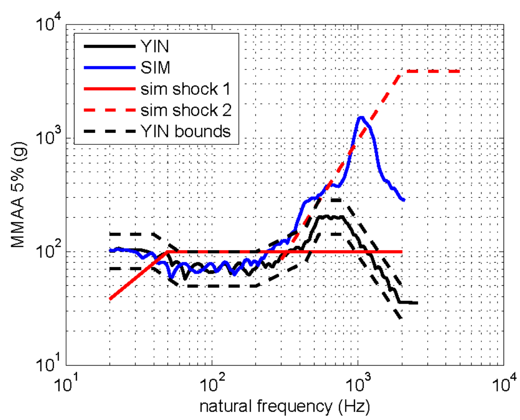
(b) Concept 1, high-frequency shock



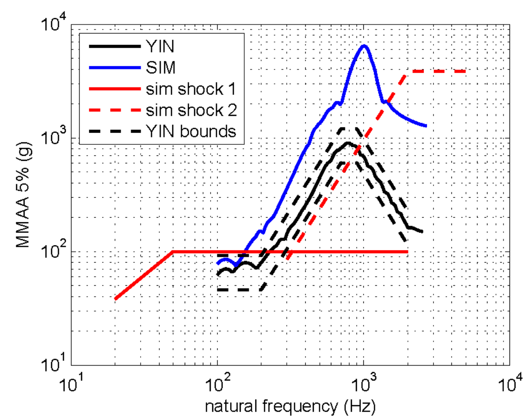
(c) Concept 2, low-frequency shock



(d) Concept 2, high-frequency shock



(e) Concept 3, low-frequency shock



(f) Concept 3, high-frequency shock

Figure 28: Shock response spectrum at electronics module for shock inputs.
(a)-(b) Concept 1. (c)-(d) Concept 2. (e)-(f) Concept 3. The design goal was to prevent the electronics module from being exposed to shock levels higher than the two shocks shown in red, which it had already been shown to survive via previous testing. Concept 3 did not meet this goal for the high-frequency shock input.

6.2.4 Design Down-Select

The FEA results summarized in Section 6.2.3 were presented to the product development team at a conceptual design review in December 2011. This in-person presentation also included an overview of the information in Section 6.2.2 on the assumptions and inherent limitations associated with these FEA models. The presentation was designed to be informative and to encourage questions from the product development team members, in order to provide an opportunity for them to better understand exactly what issues this type of FEA modeling can and cannot address. Overall, the product development team was engaged in the dialogue, with several participants asking questions at the presentation and/or following up with one-on-one questions to the investigator after the presentation. Collectively, the FEA results were viewed as confirming the design team's preference for concept 1, as summarized below.

Overall similarity of design to existing electronics assembly. Concept 1 required the fewest changes to the design of the existing electronics assembly, which had been subjected to extensive previous vibration and shock testing. The geometric similarity also ensured a minimal change in the assembly's center of gravity, and a separate assessment by the electrical engineers confirmed that the slightly-reduced height of the plug-in cards would still provide adequate circuit board area for the circuits. Independent of the FEA results, this information alone provided a strong basis for confidence that concept 1 was feasible.

Plug-in card natural frequency and vibration response. The FEA results showed concept 1 having the highest first natural frequency for the plug-in cards, which is strongly-preferred as a general characteristic for ensuring the ruggedness of circuit boards in these types of vibration and shock environments. Additionally, the vibration response of the plug-in cards was substantially lower for concept 1 than for concept 2, confirming the design team's suspicion that using thinner circuit boards for the plug-in cards was risky.

Minimizing vibration and shock levels at the electronics module. The FEA results suggested that either concepts 1 or 2 were superior to concept 3 in terms of protecting the electronics module from excessive vibration and shock exposure. The FEA also predicted that for concepts 1 and 2, the electronics module would not (for the most part) be subjected to higher vibration and shock levels than those to which it had already been tested. This fact would have been difficult to discern prior to physical prototype testing without the use of FEA.

6.2.5 Laboratory Prototype Testing

A physical prototype of concept 1, shown in Figure 29, was procured and assembled into a test unit for laboratory testing in April 2012. The unit was a fully-functional prototype and included the electronics module, shown in Figure 30, and functional circuit boards, shown in Figure 32 and Figure 31. The prototype was first used for electrical bench-top testing of the design. Next, it was attached to a test fixture (also visible in Figure 29) and subjected to vibration and shock testing using an Unholtz-Dickie T2000 electro-dynamic shaker table.

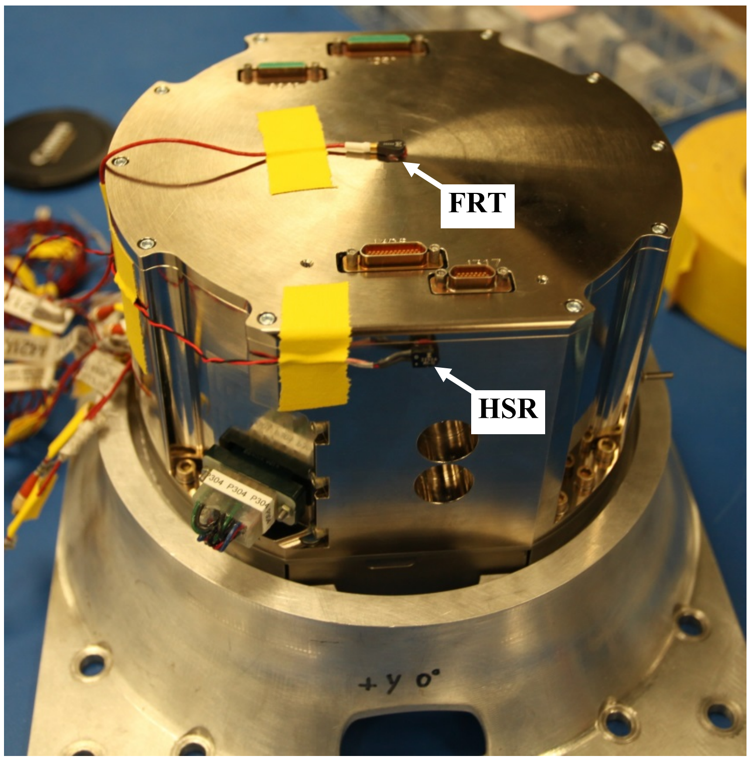


Figure 29: Prototype of concept 1.
The unit was attached to a test fixture and subjected to vibration and shock testing using an electro-dynamic shaker table (not shown). Accelerometers were bonded to the unit at multiple locations to collect data for diagnosing unforeseen behavior in the structural response and for validating the FEA model. Accelerometers were attached to the housing and cover plate (channels HSR and FRT).

During the assembly process, accelerometers were attached to the unit at multiple internal and external locations to collect data for validating the FEA model and for diagnosing any anomalous behavior in the structural response. Notable locations that were monitored included the external housing (Figure 29), the electronics module (Figure 30), the plug-in cards (Figure 31), and the motherboard (Figure 32). The response of the electronics module was monitored on its case and also on the cover plate to which it was attached, immediately adjacent to its base, which had been suggested by a design team member at the conceptual design review.

For this type of testing, Endevco 2250-AM1 accelerometers are often used, which have a range of ±500G. However, the FEA model suggested that the plug-in cards and several other locations of interest could have a response in excess of 1000G, so higher-range Endevco 2222C accelerometers were used at these locations of concern.

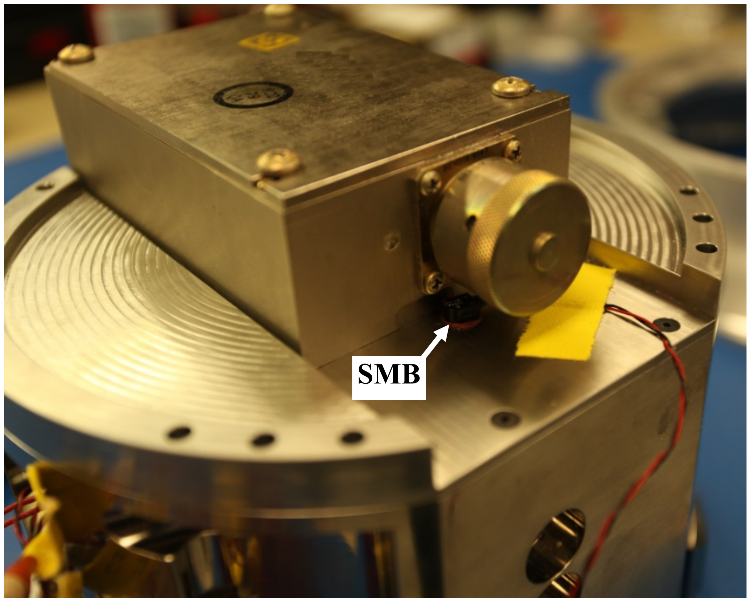


Figure 30: Prototype of concept 1, showing the attached electronics module.
The input to the electronics module was monitored on the cover plate to which it was attached, immediately adjacent to its base (channel SMB).

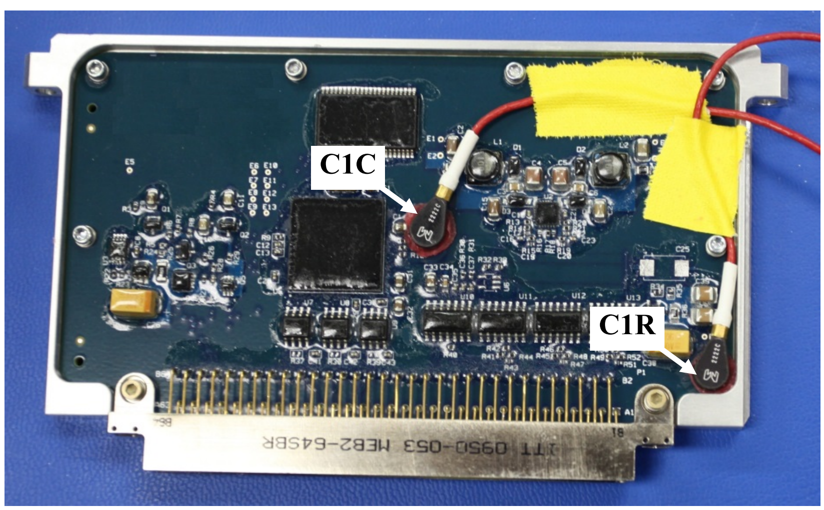


Figure 31: Prototype of concept 1, showing the first of four plug-in cards.
Two attached accelerometers are shown (channels C1C and C1R).

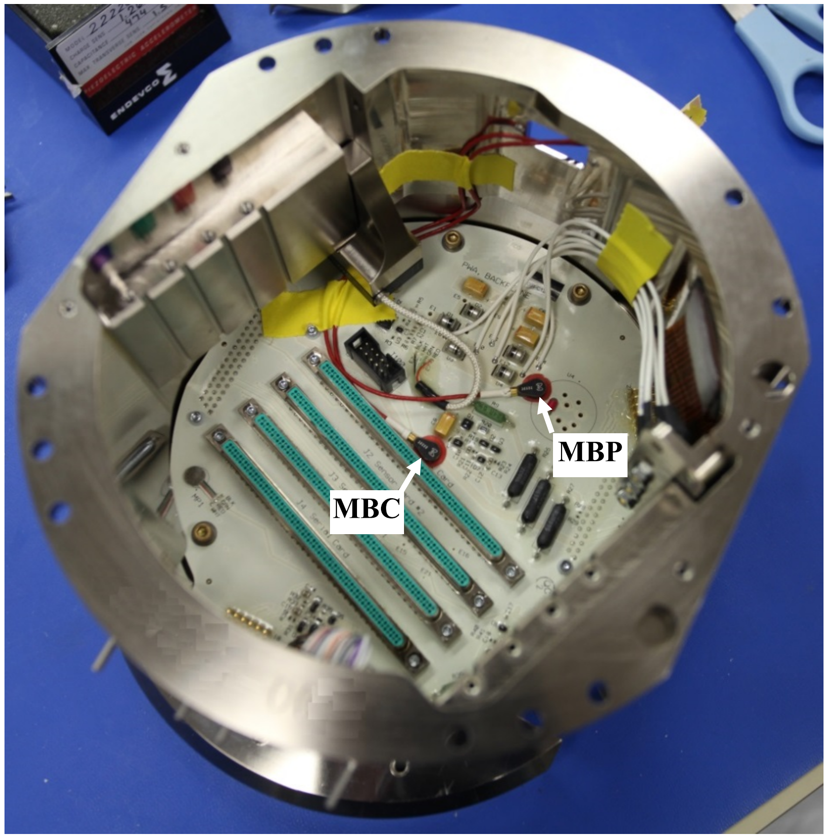


Figure 32: Prototype of concept 1, showing the motherboard.
The electronics module, one end cover, and all plug-in cards are removed in this view. The unit was a fully-functional mechanical and electrical prototype containing functional circuit boards. Two accelerometers were attached to the motherboard (channels MBC and MBP).

6.2.6 Comparison to Test Results and FEA Model Improvements

The data collected during testing was compared to the original FEA data in order to explore the accuracy of the FEA model, better understand its limitations, and gain insights on how it might be improved. This section summarizes the resulting changes to the FEA model and presents several plots comparing the original FEA model results, the prototype test data, and the refined FEA model results. The content is based on a presentation given in person by the research investigator to the other members of the product development team in June 2012, as well as a follow-on report that was distributed by email in July 2012. The in-person presentation included the comparison of test data to only the initial FEA predictions, while the follow-on report also included the comparison with the refined FEA model. Each of these instances of information sharing garnered substantial feedback from the participants, though the in-person presentation seemed more effective overall at truly engaging the participants in a thoughtful and critical discussion. The majority of their questions were focused on clarifying their understanding of what physical phenomena and types of product failures the FEA model could and could not predict, and what model parameters and details played into those capabilities and limitations. Several examples of these technical details are discussed below.

Geometry at connections between plug-in cards and main housing. As shown in Figure 33, the original FEA model predicted a first resonant frequency for the plug-in cards that was higher both in frequency and in amplitude than that observed in the prototype vibration test data. The FEA model was originally built using a circular bonded region at the location of each screw connecting the plug-in card frame shoulders to the main housing. In reality, the design utilized O-rings compressed between the plug-in card frame shoulders and the main housing, as shown in Figure 34. The intent of the O-rings was to allow the plug-in card connectors to seat fully into the motherboard connectors while accounting for tolerance stack-up in the design. The presence of the O-rings and the resulting additional free length of the screws likely makes the joint more compliant than the bonded connection in the original FEA model. The revised FEA model included the compressed O-rings and a simplified version of the screws so that the effect of the additional free length of the screws would be captured. Figure 33 shows the improvement both in terms of frequency and amplitude of the first resonance predicted for the plug-in cards.

Connections between main housing and two end covers. As shown in Figure 35 and Figure 36, the test data indicated that the first resonant frequencies predicted by the original FEA model for the two end covers were too high. The connections between the main housing and each end cover were originally modeled as bonded over the entire mated region, which resulted in the in FEA model of the end covers being too stiff. In the revised FEA model, these connections were replaced with small bonded regions between each part at the location of each connecting screw. The results for the revised FEA model, also shown in Figure 35 and Figure 36, are a better match to the test data. The motherboard is mounted directly to the inside of the front cover and is largely driven by the front cover’s response, so this improvement in the revised FEA model is also reflected in the predicted response at the motherboard, as shown in Figure 37 and Figure 38.

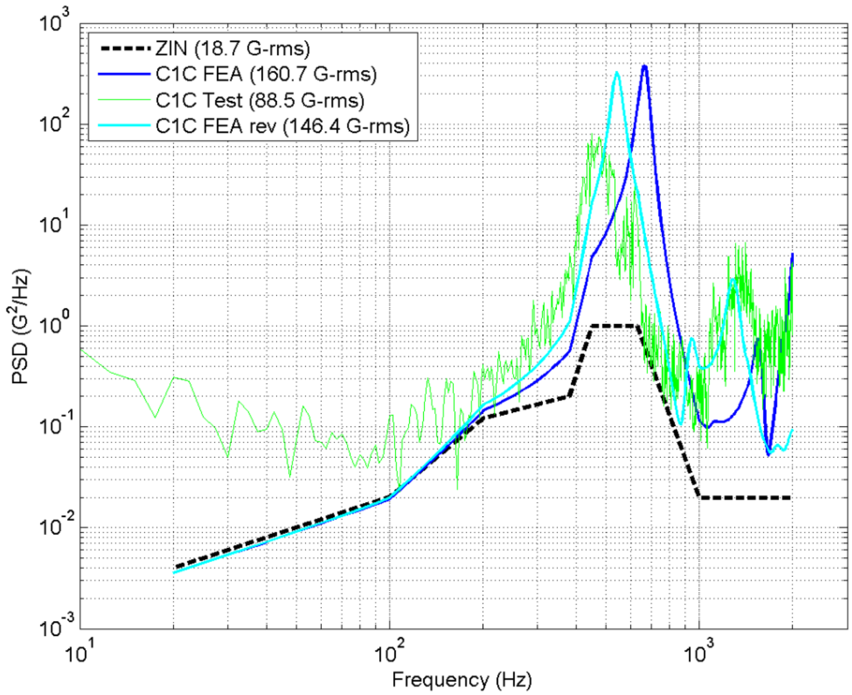


Figure 33: Random vibration response at center of plug-in cards.
Results shown for the original FEA model, prototype test, and revised FEA model. The revised FEA model included the compressed O-rings and effect of the free length of the screws. The result was a better match for both the first (approx. 700 Hz) and second (approx. 1400 Hz) resonant frequencies of the plug-in cards.

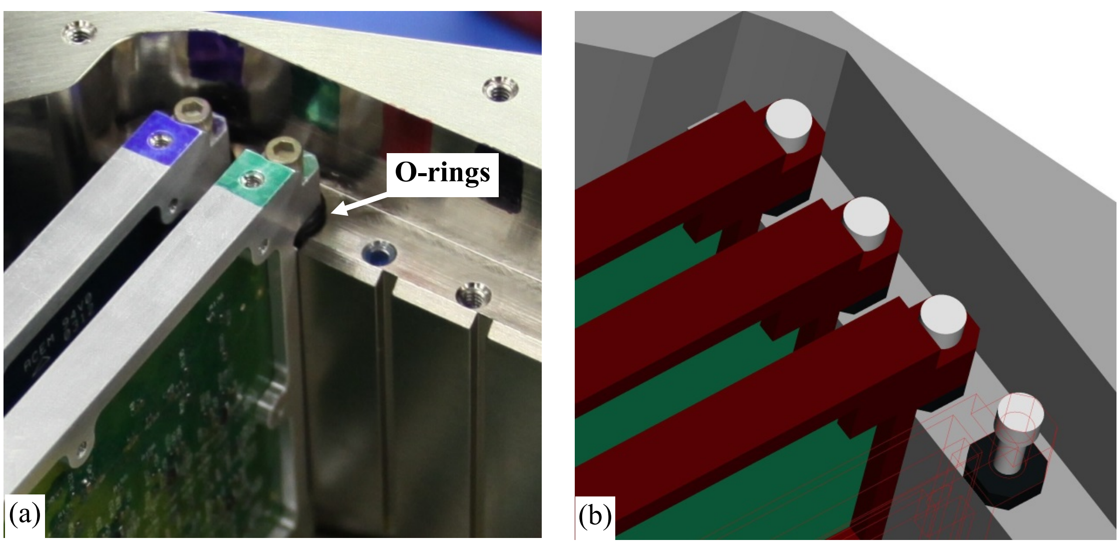


Figure 34: Plug-in card frames with O-rings under shoulders.
(a) Hardware view. (b) Geometry implemented in the revised FEA model.

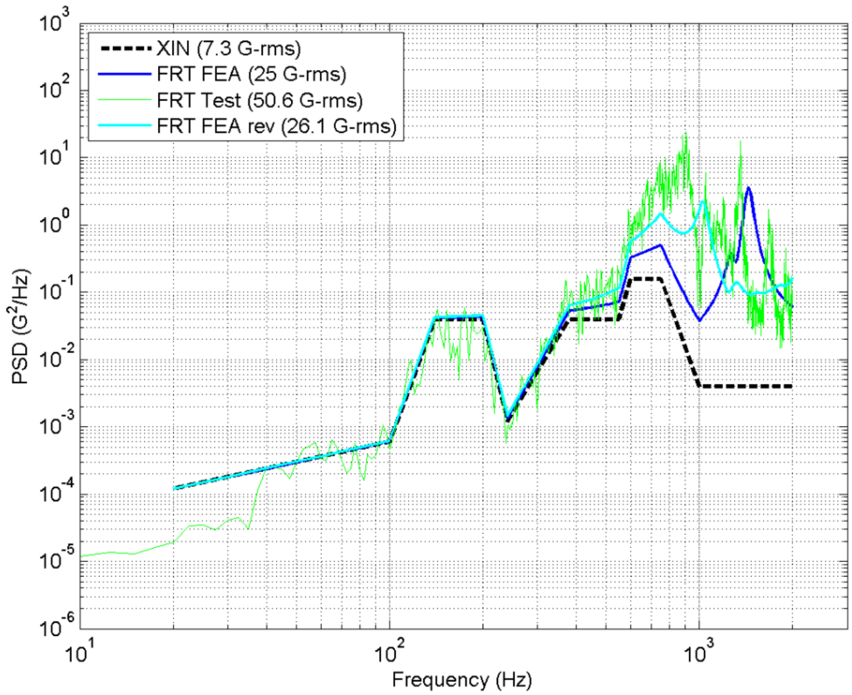


Figure 35: Random vibration response at the center of the front cover.
The revised FEA model used discrete bonded regions at the locations of screws connecting the front cover to the main housing, which resulted in a better match to the test data.

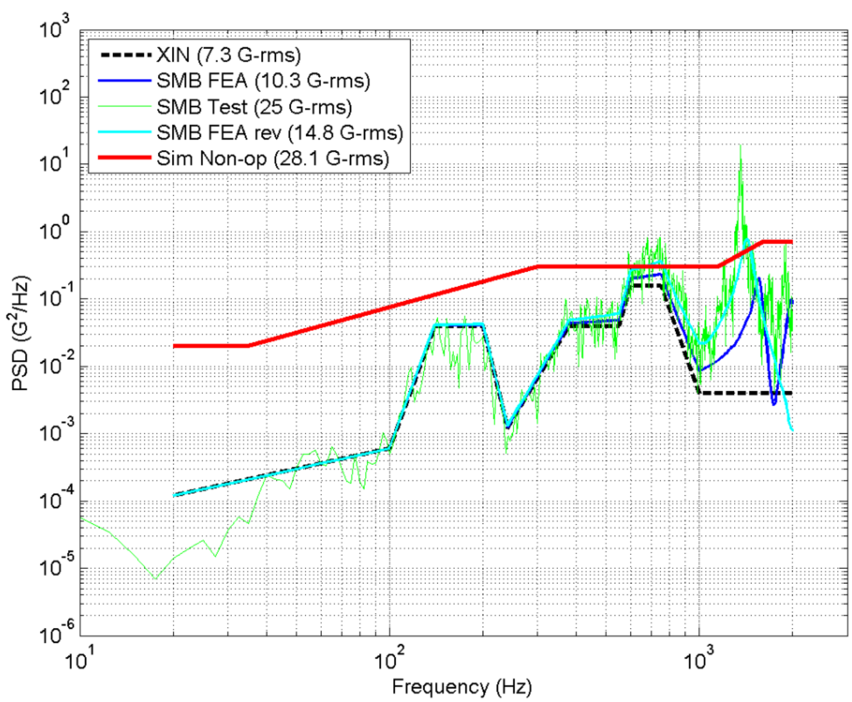


Figure 36: Random vibration response at base of electronics module.
The revised FEA model used discrete bonded regions to connect the end cover to the main housing, lowering the first resonant frequency (approx. 1400 Hz) at the base of the electronics module.

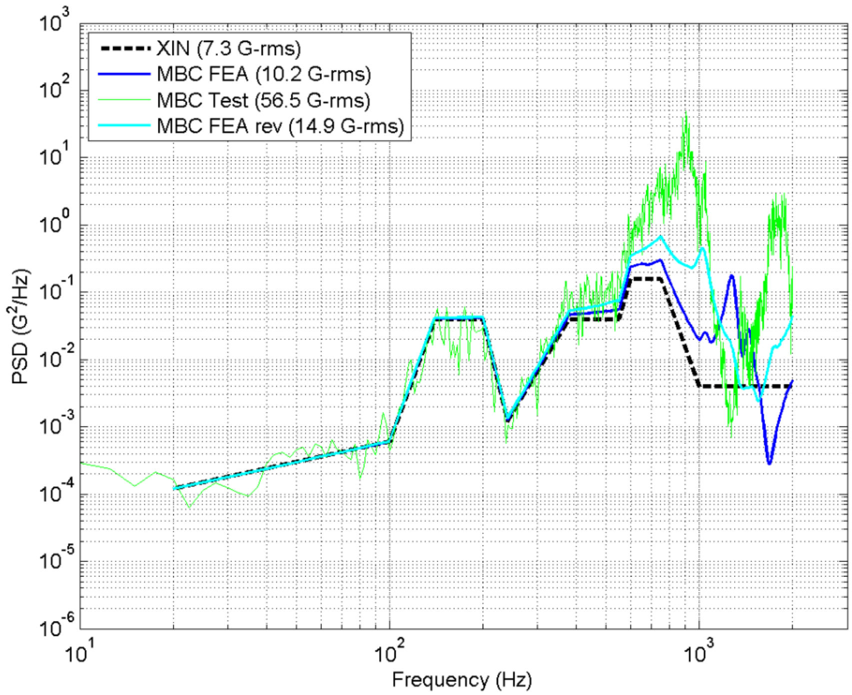


Figure 37: Random vibration response at center of motherboard.
The revised FEA model used discrete bonded regions to connect the end cover to the main housing, which coupled directly into the response of the motherboard. The match to the test data, however, is still marginal.

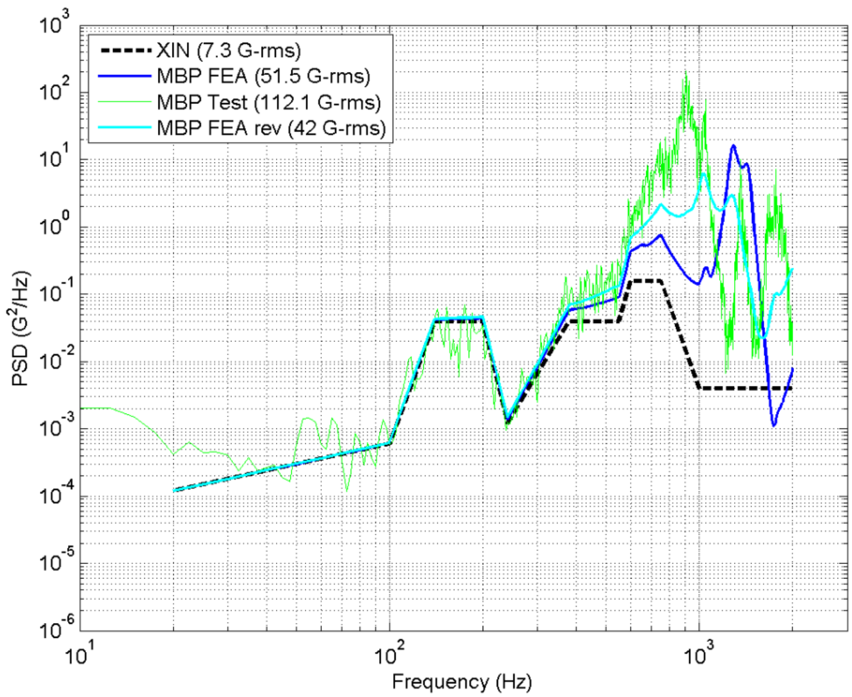


Figure 38: Random vibration response at a second point on the motherboard.
The point was located midway between the center and edge of the motherboard. Results shown for the original FEA model, prototype test, and revised FEA model.

Damping. The response predicted by the original FEA model seemed too high at the resonant frequencies at many measurement locations (for example, at the centers of the plug-in cards, as shown in Figure 33). The original FEA model used a damping value of 3%, which was based on limited historical data for similar, unpotted electronics assemblies. Increased damping values of 4% and 5% were explored for the revised FEA model, and in the end, 4% was selected as the best overall fit for the test data. This involved making a trade-off in the model accuracy at the various measurement points. For example, increasing the damping improved the model accuracy at the plug-in card centers, but reduced the accuracy at the motherboard measurement locations.

Boundary conditions to next-assembly. The original FEA model predicted a first resonant frequency for the main housing that was much too high compared to the test data, as shown in Figure 39. In the original FEA model, the boundary condition between the electronics assembly and the test fixture to which it was attached was simply modeled by fixing all six degrees of freedom of the entire mating surface, which likely resulted in over-stiffening the main housing. The revised FEA model applied the fixed boundary condition only at small discrete regions where the screws are located for attaching the housing to the test fixture. The resulting improvement in the revised FEA model is evident in Figure 39, although the first resonant frequency is still too high. It is suspected that this further discrepancy was due to the issue of 'where' the boundary condition was drawn—that is, how much of the test setup was included in the FEA model. Often, test fixtures are quite stiff, and as such can be omitted from FEA models and instead 'replicated' with simplified boundary conditions. However, this particular test fixture (visible in Figure 29) was designed with the intent replicating the stiffness of the next-assembly structure. It was much thinner and more compliant than a typical test fixture, and as such, its effects are more difficult to capture without including it in the FEA model. An attempt was made to include the fixture in the revised FEA model, but limitations of the FEA software were encountered. In Mechanica, there is no way to specify the acceleration loads at one location (the 'control' point where the electronics assembly is attached to the mounting flange of the fixture) while applying the force loading at another location (the bottom of the test fixture, where it mounts to the shaker table).

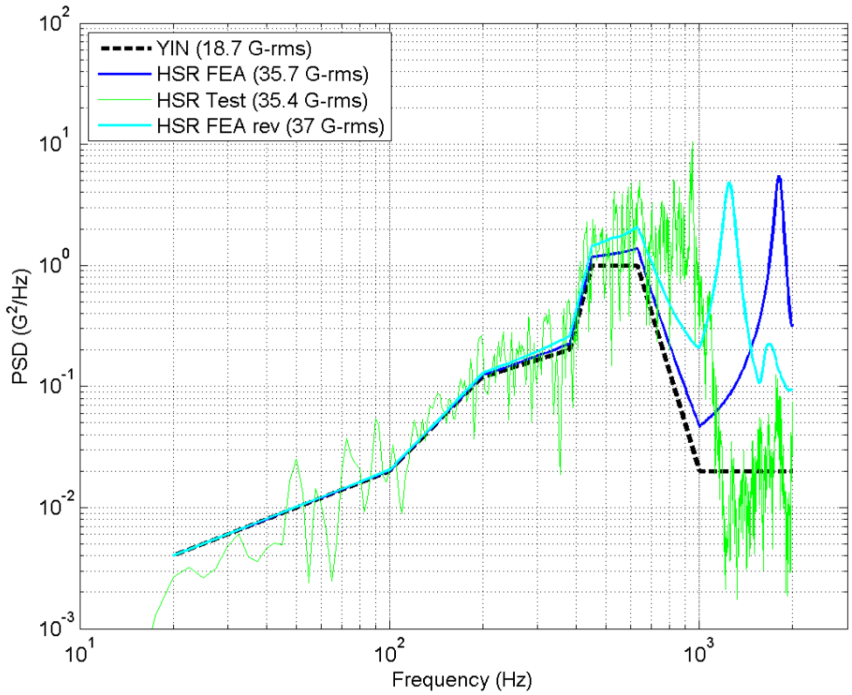


Figure 39: Random vibration response on the side of the main housing.
The revised FEA model applied the fixed boundary condition only at small discrete regions where the screws are located for attaching the housing to the test fixture. The resulting improvement in the revised FEA model is evident, although the predicted first resonant frequency is still too high. This is likely due to the use of a 'compliant' test fixture, whose effects are not captured by the FEA model.

Element types (connections) for plug-in card connectors. From the beginning of this FEA effort, the research investigator recognized that modeling the mechanical effect of the electrical connectors between the plug-in cards (visible in Figure 31) and the motherboard (visible in Figure 32) would be difficult. The original FEA model used a combination of beam elements to model the bending stiffness of the aluminum shells and Mechanica 'rigid link' elements to model the connection stiffness, as depicted in Figure 40. The complexity of the mechanical interaction is best visible in the vibration response at the corners of the plug-in cards near these connectors, shown in Figure 41. An alternate modeling method was investigated using very stiff springs in place of the rigid link elements, but this change actually made the model worse. In the end, the revised FEA model was left unchanged from the original in this regard.

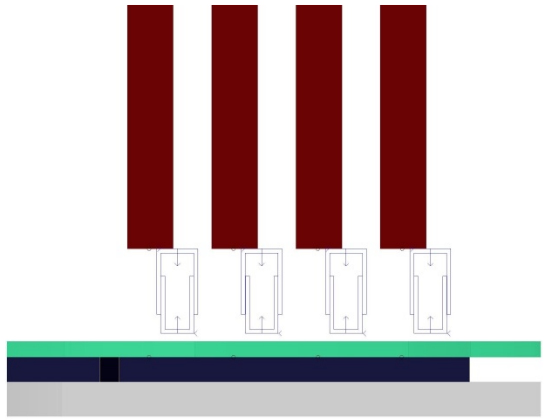


Figure 40: Cross-section of FEA model showing details of plug-in card connectors.
The front cover, motherboard, plug-in card frames, and beams cross sections used to model the electrical connector shells are shown. Mechanica 'rigid link' elements (not visible) were used to model the connection stiffness between the cards and the motherboard.

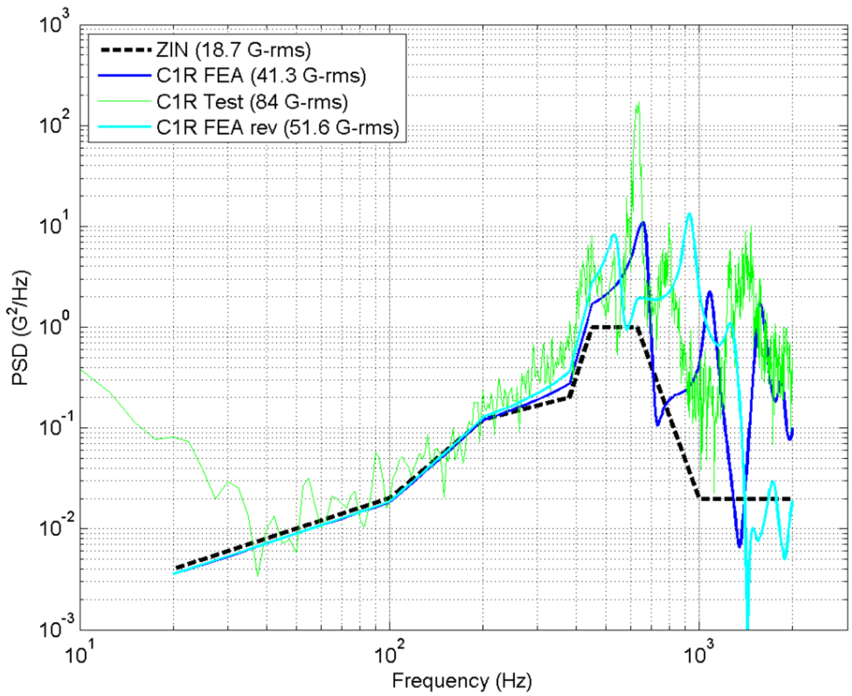
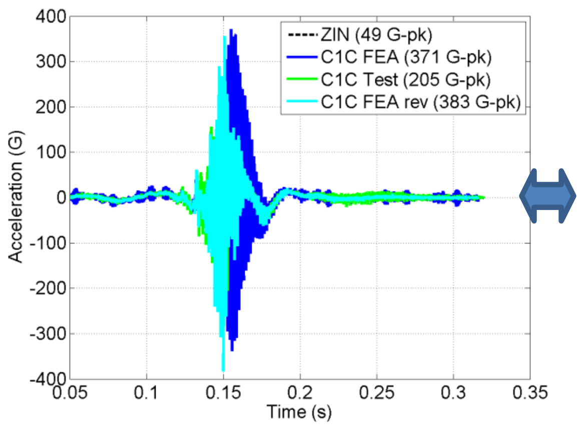


Figure 41: Random vibration response at lower corner of plug-in cards.
The complexity of the mechanical interaction at the electrical connectors between the motherboard and the plug-in cards is evident, and clearly is not well-captured by either the original or revised FEA models.

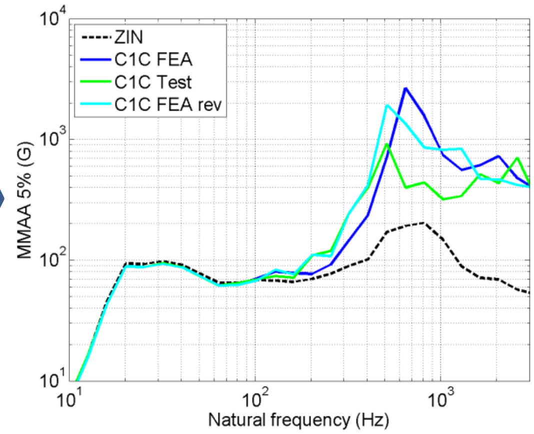
Response in shock environments. Example responses to low- and high-frequency shock inputs are shown in Figure 42 and Figure 43.[12] In general, the FEA models were more

[12] Shock requirements were expressed as shock response spectrums (SRS). Acceleration time histories must be generated analytically that satisfy SRS requirements. An initial set of time histories was generated for the purpose of running the original FEA models. Shaker table shock testing of the prototype unit was performed using a different set of time histories, which were in turn used for the

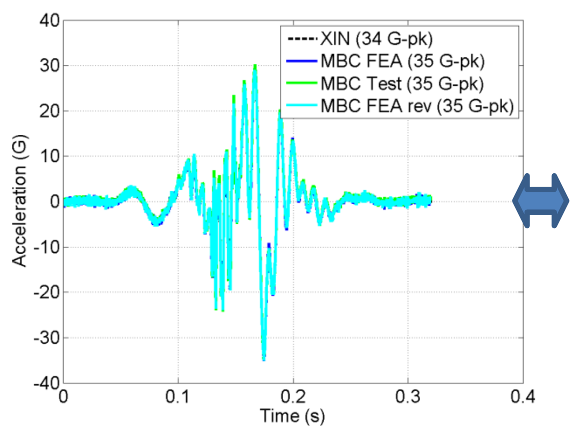
accurate for the low-frequency shock environments than for the high-frequency shocks. This is due to the fact that the modal analysis results are more accurate for lower natural frequencies and their associated mode shapes, but tend to fall off for higher natural frequencies.



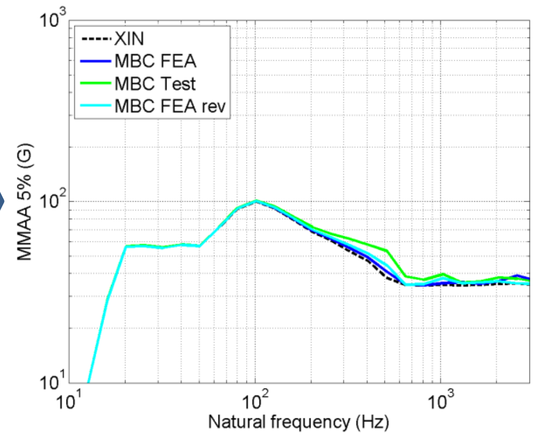
(a) Low-frequency shock, center of plug-in card



(b) SRS, low-frequency shock, center of plug-in card



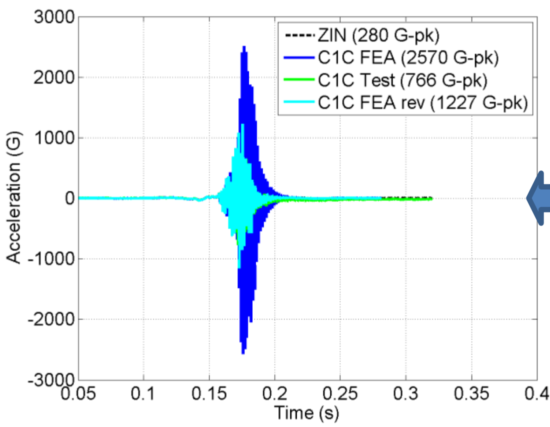
(c) Low-frequency shock, center of motherboard



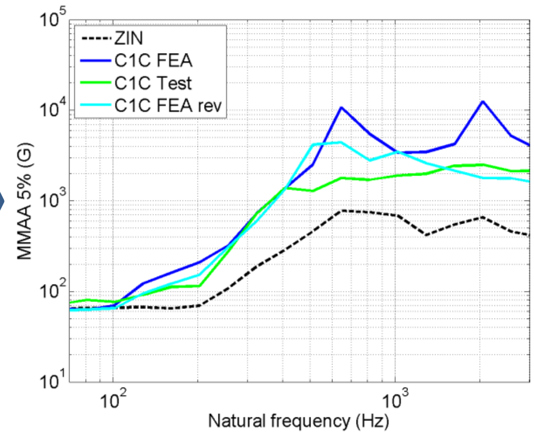
(d) SRS, low-frequency shock, center of motherboard

Figure 42: Example comparisons of response to low-frequency shock input.
Overall, the FEA model was more accurate for predicting the response to low-frequency shock inputs than for high frequency. (a)-(b) Response at center of plug-in card is over-predicted. (c)-(d) Response at base of electronics module correlates well with test data.

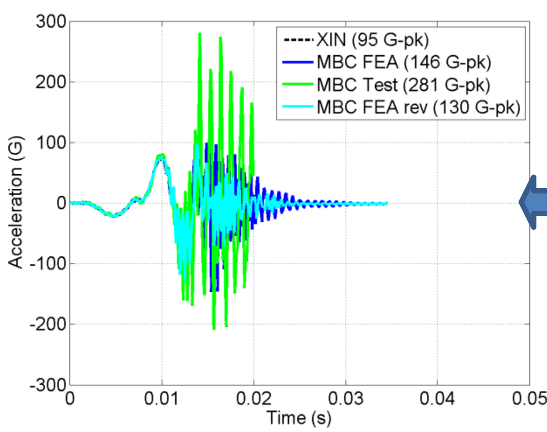
revised FEA model. To facilitate a comparison to test data and the revised FEA model, the original FEA model was re-run using the acceleration time histories generated for testing.



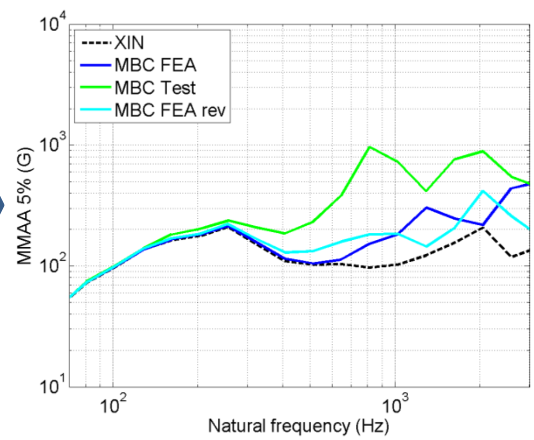
(a) High-frequency shock, center of plug-in card



(b) High-frequency shock, center of plug-in card



(c) SRS, high-frequency shock, center of motherboard



(d) SRS, high-frequency shock, center of motherboard

Figure 43: Example comparisons of response to high-frequency shock input.
Overall, the FEA model was less accurate for predicting the response to high-frequency shock inputs than for low frequency. (a)-(b) Response at center of plug-in card is over-predicted, although the revised FEA model shows some improvement. (c)-(d) Response at base of electronics module is under-predicted.

6.3 Findings

The FEA survey data, the first FEA interview data, and the investigator's case study field notes were analyzed per the method described in Section 5.6. This section describes the main findings resulting from that analysis, with supporting case study data directly cited to help illustrate and support the findings.

Section 6.3.1 discusses the themes of confidence in FEA and confidence in the person performing the FEA. Section 6.3.2 discusses how participants primarily viewed FEA as a means to obtain design confidence. Section 6.3.3 discusses their lingering concerns about the amount of time required to use FEA, and Section 6.3.4 describes their evolving appreciation for the trade-offs between FEA accuracy and assumptions. Section 6.3.5 summarizes the effectiveness of communication about FEA within the product development team. Section 6.3.6 discusses the strong influence that previous encounters with FEA had in shaping the participants expectations and views, which was an important and unexpected theme that emerged. Finally, Section 6.3.7 summarizes evidence that the study participants became more open to supporting the use of FEA in their future projects as a result of their experience on this project, and Section 6.3.8 presents examples of the case study participants conceiving of possible applications for FEA on their own.

6.3.1 Confidence in FEA Must Be Earned

The idea of 'confidence' emerged as a strong theme in the data. The term appeared in the guided interview protocol, but was used by the participants in their responses with a much greater frequency than was anticipated. Of the terms included in the word frequency chart shown in Figure 44, 'confidence' was the fourth most common (after the much less surprising terms 'design,' 'testing,' and 'FEA').

In addition, 'confidence' had a much richer usage by the participants than was used in the interview protocol, which really only used it to ask about the participant's confidence that the physical prototype would successfully pass vibration and shock testing. One of the usages by the participants was to speak of their confidence *in FEA itself*. Their comments indicated that confidence in FEA is not inherent or automatic, but is instead earned.

> Initially, I was just very much in my electrical engineering world, and I didn't use FEA, and so… I just didn't have confidence in it. … I walked in thinking, "yeah, analysis is great, but it's on the side".
>
> Participant 5, end of case study 1

> I think this is important for FEA engineers, is that they have to be able to establish this confidence in this analysis in programs, because if they don't, all their work is practically wasted… every time you start a new FEA project, you kind of have to start over… You have no chance of improving your model because nobody cares.
>
> Participant 6, end of case study 1

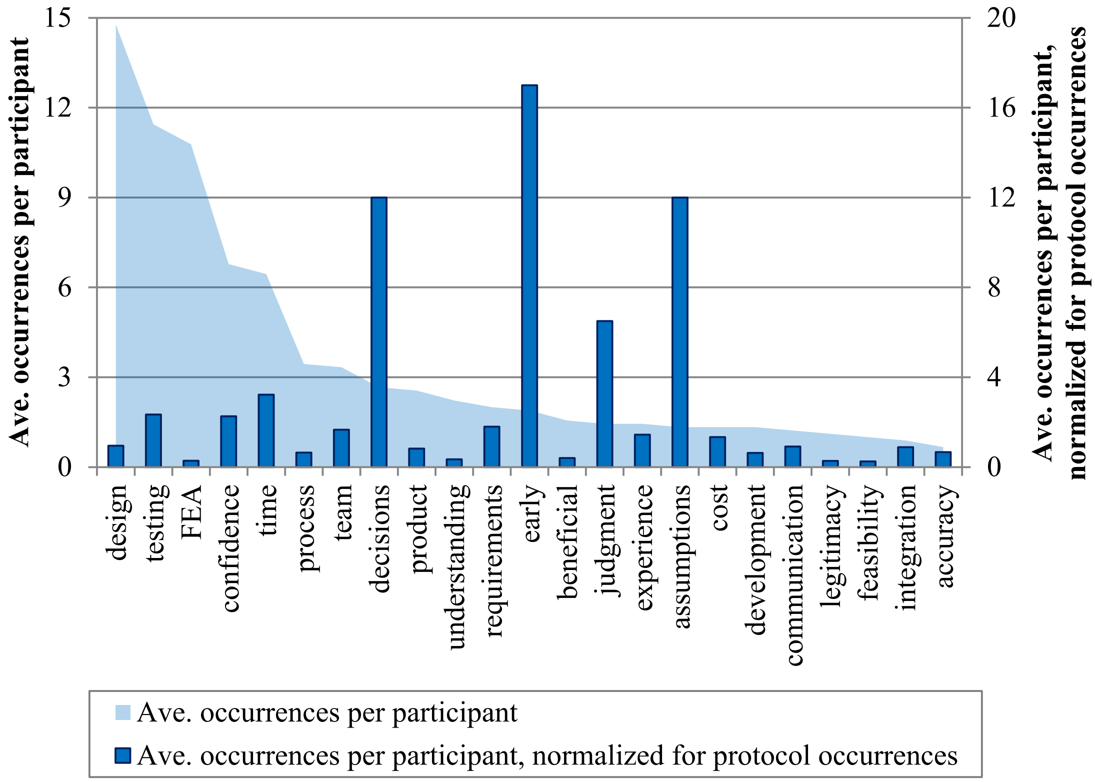


Figure 44: Case study 1 word counts, taken from 1st interview transcripts.
Terms are sorted beginning with the most frequently-occurring on the left side of the chart. The word counts are also shown normalized for (i.e., as a ratio of) the number of occurrences in the interview protocol, as an indicator of topics that participants considered important. 'Confidence' was an unanticipated but prevalent theme revealed by the raw (non-normalized) counts. 'Early,' 'decisions,' 'assumptions,' and 'judgment' are clear standouts in the normalized counts.

Participants tended to attribute their confidence in FEA to one of two factors. The most common factor was being able to see a direct comparison of the FEA results to experimental test data, as illustrated in the following comments.

> I think some kind of testing to go along with the FEA model, or at least parts of it is necessary, especially for a more complex system. Once part of the FEA model is valid, adjustments can be made with more confidence.
>
> Participant 7, beginning of case study 1

> One thing that surprised me was that the FEA results were directly comparable to our vibe and shock data. You could really put them side by side and do a direct comparison. So that was interesting.
>
> Participant 4, end of case study 1

> You know, then I started to really look at the results, and I really looked at, early in the design, what he was doing, and it felt like, it should be a part of every

> project. Like, it made me… no matter what, I think even if you do have the time to test, you should match your analysis with your testing. And with that, you can build confidence in your models.
>
> Participant 5, end of case study 1

> In my future designs, I would certainly put [FEA] under my consideration… because of the confidence that [the FEA analyst] has built for [this] project. … He built a lot of confidence in me by correlating his results with the real world results, it definitely builds more confidence, and I think it's more feasible in the future knowing that this can be done.
>
> Participant 6, end of case study 1

One participant attributed their overall confidence in FEA to exposure on a previous project in which test data were used to validate and build confidence in an FEA model.

> I was involved with [FEA]… on a project many years ago where we were designing a very large containment system that was designed to go through actually an aircraft accident and a fuel fire and have the contents survive. And so that was where I got a really good, I think, view of how the FEA and the modeling and the testing all gets tied in together, because we would have the experts in the modeling and analysis build up the model, we had the funding then and the time to go and take our test equipment and go out and test it, and then go back and adjust the models. … We got to the point where we could extrapolate that model out a long way and still feel comfortable that it was giving us accurate information. So that was really where I saw how good, I think, FEA could be, and how much of a benefit it could be to a program.
>
> Participant 1, end of case study 1

The other factor to which confidence in FEA was attributed was yet another usage by the participants of the word 'confidence': an overall confidence *in the person* performing the analysis. For example, when asked what factors affect their impression of the credibility of FEA results, one participant responded with a litany of questions primarily focused on their impression of the FEA analyst.

> Do the results and my engineering intuition agree? Do I know the analyst? Do other experts know the analyst? Trust the analyst? Can the analyst discuss the results in a broad context? Do they understand the physical product/situation they are modeling? Can they explain the assumptions they made and the effects they had on the results?
>
> Participant 9, beginning of case study 1

Another attributed confidence in FEA to both factors: the comparison to experimental test data and the person performing the FEA.

> Models aren't quite perfect yet, and that's a really hard thing to do—to get a good model. … You know, as the computers—and people's knowledge of how to use them—gets better… we're going to keep moving in that direction. … For someone with better knowledge and experience, then as you get [test] results, you can refine the models, which leads to even better results and thus greater legitimacy. And part of that is who you've got doing it. I think people's experience with [FEA], and how they follow up with it [is important].
>
> Participant 2, end of case study 1

6.3.2 FEA Viewed as a Means to Obtain Design Confidence

Participants often connected the use of FEA to the need to obtain confidence *in the design*—i.e., that it would meet its functional requirements during exposure to vibration and shock inputs. This was the third distinct usage of the term 'confidence' by the participants and essentially the same as that used in the guided interview protocol.

> From my vantage point, [the use of FEA] was all about gaining confidence. … We need to come up with an idea… in a very short period of time, and we have to be confident that it's going to work.
>
> Participant 8, end of case study 1

> When [the research investigator] presented his first results, showing us how the [plug-in] cards would behave during the environments that we specified, I was pretty confident that it was going to work. We didn't see anything that jumped out at us… as far as the mechanical design is concerned.
>
> Participant 6, end of case study 1

Several participants specifically mentioned the need to develop confidence *in the decision* to select Concept 1 (Figure 17) over the other concepts (Figure 18 and Figure 19). The importance of this theme is also evident in the high normalized word count results for the terms 'decisions' and 'judgment,' as shown in Figure 44.

> The FEA analysis really allowed us to confirm that we were making the appropriate decision at the first try, which I think was a big benefit. … So we had really good confidence in being able to say, okay, we chose the best location [for the electronics module, Figure 14 and Figure 30] and we have confirmation from a proven FEA analysis technique.
>
> Participant 5, end of case study 1

> There was kind of like one or two or three different paths we could have gone down on, and the FEA sort of confirmed that the path we were going down was okay. I don't think it necessarily led us down that path, because we were led down that path for other reasons. But I guess it made us more confident that that was a good path to go down.
>
> Participant 7, end of case study 1

> I think [the team] already had a good idea of which direction they were going to go, but [FEA] helped confirm their decisions—and then put tangible numbers behind them as well.
>
> Participant 9, end of case study 1

The similarity of the design (Figure 29) to the original electronics assembly (Figure 14) contributed strongly to the team's design confidence, which in turn affected the participants' views of the specific role that FEA played on this project.

> There was some similarity, there were some modifications, so… I had strong confidence in that we weren't doing a complete redesign, and a completely new technique. It was just a modification of something that we've done before. So that gave me stronger confidence.
>
> Participant 5, end of case study 1

> This design was an existing design that we were using with small modifications for this new application. And so we had a fair amount of trust in the design already. But we did have to make a design change, and the FEA helped us with confidence in that design change.
>
> Participant 4, end of case study 1

Several participants, when asked directly about specific benefits or impacts on the product design as a result of using FEA, brought their responses back around to this general idea of using FEA to confirm decisions and build design confidence.

> I think [the design team] had some good engineering judgment going into it—about design decisions, and so forth—and so the FEA, in this particular case, I don't think brought to light things that they didn't know, but it confirmed those decisions and assumptions about what they were doing. So then it provides more credibility to their design decisions and the direction they went.
>
> Participant 9, end of case study 1

> I think [FEA] gave them confidence in their original design. … Actual impacts? Probably not… It was more of a confidence level.
>
> Participant 11, end of case study 1

> [The impact of FEA] was more of a confirmation, almost, I felt, that we were doing the right thing. There is an instance which we're planning to still use it, which I think is kind of a better illustration of this, where we've already gone through one round of testing so far, and we're making some changes to some parts… And we don't necessarily want to retest, because everything is so similar, so we were planning to… take these changes, kind of incorporate them into [the] FEA model, and see if there's any kind of appreciable change in the [vibration or shock] levels that we see. And based on that, we can kind of make a judgment whether testing is necessary or not. I mean, we feel like it's not necessary, but I think this will give us kind of more evidence and more confidence that it won't be.
>
> Participant 7, end of case study 1

One participant abstracted the discussion in a very insightful way, describing the complementary roles of engineering judgment and engineering analysis techniques such as FEA.

> Initially, we had chosen [design Concept 1] based on engineering judgment. … I guess I'd like to see, typically, as an engineer, some quantitative results that say, "our engineering judgment matches our analysis." … Engineering judgment is great… I think it really helps us make some decisions early—but I think typically that's going to be the first step, and your second step is going to be to go and perform some sort of analysis on what your engineering judgment was. … I think you can't really have one without the other. You can't start the process without engineering judgment, and you can't prove your engineering judgment without some sort of analysis.
>
> Participant 5, end of case study 1

Interestingly, the data also suggests that design team members are keenly aware when, for one reason or another, FEA is *not* serving the purpose of obtaining design confidence.

> For a class design project [FEA] was a requirement with little verification of the model. It was done more as an exercise in doing it, but it added no value to the overall project. … I was also tasked with doing some FEA at work. It turned out just to be busy work and the parts I was doing analysis on were already in production.
>
> Participant 7, beginning of case study 1

> What I saw on [a] previous program is that FEA results just came in way too late. The design was done, it was already in production, and now I saw this thermal analysis of my, you know, my design… it almost doesn't matter anymore. It's almost like, money wasted… especially in that case—it was that [the FEA results] came in, and they didn't see any problem. And you're like, okay, well I already know that, because I had already proven it in the actual qual [i.e., qualification testing].
>
> Participant 6, end of case study 1

> [In the past, FEA failed to benefit a project] when the complexity of the FEA was driven not by project/product needs, but by programmatic needs—dictating that FEA "must" be used, or that certain codes "must" be used, or that a certain number of elements "must" be used… to promote other programmatic objectives.
>
> Participant 9, beginning of case study 1

6.3.3 Persistent Concern About Time Required for FEA

At the beginning of this study, participants were asked about the length of time required to use FEA, and whether it typically leads, lags, or keeps pace with design activities. The responses were somewhat muted, but foreshadowed what would eventually become a theme in the data.

> I would imagine it would be difficult for FEA to keep pace with design activities.
>
> Participant 4, beginning of case study 1

> The cases where I've seen [FEA] used was to help solve problems after the design was complete. So it lags.
>
> Participant 2, beginning of case study 1

> I was… tasked with doing some FEA at work. It turned out just to be busy work and the parts I was doing analysis on were already in production. … My current experience seems to suggest it lags, or it is being used as a way to validate what was seen in the testing with no other application.
>
> Participant 7, beginning of case study 1

> [FEA results are useful] when information can be obtained quickly.
>
> Participant 9, beginning of case study 1

At the end of the project, several participants reflected back to the beginning and discussed this issue in more detail, recalling a feeling of concern about how much time would be required to complete the FEA.

> I think people tend to shy away from FEA just because there's an initial investment—a time investment. … I was a little intimidated by how long it would take to make that model. A lot of times, oh, it's a huge effort to make a model.
>
> Participant 5, end of case study 1

> Just knowing how long it usually takes for FEA results to come out, and how fast we're going on this project, I didn't think it was really that feasible.
>
> Participant 6, end of case study 1

> I don't have a lot of experience, and I wasn't sure, without spending months on [the FEA], how good of results we could get.
>
> Participant 7, end of case study 1

> I was slightly skeptical because I had never seen the FEA analysis done on something that didn't exist. So [the analyst] would have to put everything together and then do the modeling. And I was more concerned about the timeline than the ability to do it. In my [previous] experience, it took a long time to build the model—to get all the programming and the numbers correct, all the math correct so as to have a capable model. And so I was just a little skeptical that it could be done in time, rather than if it could be done.
>
> Participant 8, end of case study 1

Over the course of the project, two participants separately approached the research investigator to get more information on how long it took to perform some of these FEA vibration and shock analyses. Their questions gave a clear sense they were assessing in their own minds whether or not it is feasible to use FEA within the time constraints of a real product development effort.

The prevalence of time as a theme in the data is also confirmed in the word frequency chart (Figure 44), in which 'time' is the fifth most common term used by the participants in their interview responses, right after 'confidence.' It also has a relatively high normalized value (a little more than three), meaning that it was used by the participants in their responses about three times as often as it was used in the guided interview protocol. The term 'early' had the highest normalized value at 17—a reflection of the fact that it was barely used in the interview questions, but was used on average about two times per participant in their interview responses.

Regarding the use of FEA in this case study, the participants seemed to feel collectively that FEA was used within the time constraints of the project, as illustrated in the following quotes.

> To my knowledge, I think it only took [the research investigator]… you know, it took him some time to develop the model, but I think overall, he had a lot of the ins and outs of the model developed. So I think that the analysis itself wasn't a major, major effort. I think it was something that he was able to perform on his own in a reasonable amount of time.
>
> Participant 5, end of case study 1

> I don't think it's an issue in this [project], but I think that's something any engineer who is doing FEA would have to watch out for. … They really have to keep up with the program if they want their results to be considered in the program. That's really the only issue that I would see… but not in this case.
>
> Participant 6, end of case study 1

> Looking at it now, I'm happy with the results we got from this initial FEA study, so now I see [FEA] as slightly more feasible.
>
> Participant 7, end of case study 1

> [This project] supported my view. So if we didn't get information back [from FEA] within, you know, 'weeks' timeframe, then it wouldn't have been useful, because the team was moving ahead.
>
> Participant 9, end of case study 1

However, despite the experience on this project, some of these same participants attached caveats to their observations.

> I think it's worth the time, but it's hard to get that time when you're on a fast-paced project.
>
> Participant 4, end of case study 1

> [The FEA analyst must] keep up with the rest of the project—meaning that when he's doing his analysis, he really has to present his progress. … From my previous

> experience, you come into a few issues when you are looking at FEA, is either the program is running out of money, and they don't want any more analysis done—they only want actual testing done—or that an engineer who is performing FEA is taking too long, and no one cares about the results because the actual testing results have already come in.
>
> Participant 6, end of case study 1

> [Using FEA on a project like this one has] been done—it is feasible. Um… but I would caveat that with saying you need the proper resources. You need someone like [the research investigator] to be able to do it.
>
> Participant 8, end of case study 1

> I think if you can overcome the budget and scheduling, I think I would find [FEA] more favorable now. … I think—and it's my perception–that developing the model takes quite a bit of time, and the labor cost associated with that.
>
> Participant 11, end of case study 1

So there appears to exist some hesitancy on the part of the design team to translate their specific observations or experiences on this project into general beliefs that FEA can be utilized within the time constraints of a typical product development effort.

6.3.4 Trade-offs: Accuracy, Assumptions, and Design Process Integration

In the FEA survey at the beginning of the project, five of the participants were asked if they had ever seen FEA results presented that did not seem trustworthy or accurate.[13] Participants 1, 4, and 5 responded 'no,' all three of whom were electrical engineers who had never used FEA themselves. Participants 7 and 9 responded 'yes,' both of whom were mechanical engineers who had themselves used FEA in the past. Participant 7 elaborated with the following comment.

> I think it is a good tool, but I've become increasingly wary of trusting [FEA results], at least when I try some analysis. It seems to me that many small errors/bad assumptions could creep in and greatly skew the results.
>
> Participant 7, beginning of case study 1

So although the available data are limited, it appears that much of the team may not have been initially familiar with (or focused on) the idea of FEA having limited accuracy.

[13] Only five of the nine participants received this question, due to the use of survey logic.

At the end of the project, the team members seemed reasonably satisfied with the level of accuracy obtained in the FEA models.

> Well, you know, accurate is… it's almost like, alright, define accurate? … If you're within 10 percent, or 2 percent, or whatever? I think [the FEA results] were fairly accurate, even though there were some points in the model versus the actual data that were off, but I think overall, it did truly reflect what we saw when we went and ran the tests.
>
> Participant 1, end of case study 1

> We saw some slight discrepancies in the FEA results, and it was useful to understand what those discrepancies were, and I think it was mostly related to the model that we used for the FEA didn't have all the features that the actual unit has. He had to simplify the model, so the fidelity was slightly lower, or different, and the results were slightly different. So it wasn't a big deal, but we did see some discrepancies.
>
> Participant 4, end of case study 1

> We went back through the results and looked at the analysis versus the actual confirmed [test] results, and it was really interesting. A lot of the analysis matched right on with the actual testing that we did. So the results in hardware were the same as they were in software in a lot of cases. … There were a few that were inaccurate, but they were at certain high frequencies… The model maybe broke down a tiny bit… you know, just as you would expect for any model. … It made me look at analysis as saying… there are less flaws in it than I would typically think an analysis would have.
>
> Participant 5, end of case study 1

> There is some inaccuracy that [the research investigator] presented in his results, [but] as far as an electrical engineer is concerned, it looks pretty well correlated with the test results.
>
> Participant 6, end of case study 1

> I think there were a couple channels on the accelerometers which seemed a little off… I don't remember which ones exactly, but I didn't think they were that important. It seemed like the important ones sort of matched up to the test data, which ended up, I think, being pretty good. … I was actually pretty surprised at how accurate he… got it, in the kind of qualitative sense. But a lot of the peaks of all the frequencies were close to where they actually were, and matched up with the test data, you know. And he didn't need a team of people working on a model for months to actually

> accomplish that. So that was kind of… I don't know if it was 'surprising,' but it was good to see that that's possible with even kind of—you know, not the kind of big, high end FEA software, but something we could do from our offices, basically.
>
> Participant 7, end of case study 1

Several of the participants observed a relationship between the level of accuracy achieved with the FEA models, the assumptions involved in building them, and the overall amount of time required to use FEA. Moreover, they made a connection between this 'time' factor and the extent to which FEA can be integrated into the product design and development process.

> It seemed difficult to figure out which features were critical to having a high-fidelity model and which features weren't. … You have to trade-off between which features you want to model and keeping the model simple, so that it's a quick simulation. So trying to figure out which features are necessary and which features aren't seemed like a challenge. And so without a lot of time, I don't know if [the research investigator] was able to spend a lot of time on that fine-tuning process. … So that seems like the biggest challenge with FEA keeping up with the design process, is just trying to fine-tune the model as you go along.
>
> Participant 4, end of case study 1

> [FEA is] actually very hard work! I assumed before, based on the thermal analysis that I've seen, that you plug in a few parameters, and the software would have programs—algorithms—that calculate everything for you. But from what [the research investigator] described, it's like he actually had to model the components, put in his assumptions… it's like the number of parameters is way beyond what I thought. So, it's very complex, and I understand now why it takes so long, and why some projects wouldn't even bother doing this. It's very difficult.
>
> Participant 6, end of case study 1

When asked how FEA could be made more beneficial to a project like this one, Participant 9 responded with a thought that ties together the ideas of using FEA for design guidance, relative (rather than absolute) accuracy, and the need for FEA to be quick.

> In our business world, [we need] to develop those tools that can be used up front for the conceptual tradeoffs—so very quick. It doesn't have to have an absolute answer, but provide guidance: "This looks like it's going to be worse than that," you know, "this is much better." So having a lot of belief in the model, even if the model is

> just giving direction. So I think that is the place where we can benefit the most.
>
> Participant 9, end of case study 1

Interestingly, when Participant 7 was asked about their initial view that FEA results could be "greatly skewed" by "many small errors/bad assumptions," a somewhat moderated view was evident in their response.

> There were some things—basically, more on boundary conditions—how this unit was mounted to a test fixture, for example, and that test fixture wasn't modeled, but it had to be kind of modeled in the boundary condition. And I thought that would have more effect than it actually did, just looking at the results. … The FEA was kind of refined as we went on, and some changes were made, which made it better, and then kind of moved the FEA results closer to the test results—kind of a validation. So, in that sense, it was still kind of changing small details to change the model, but it had less of an effect, I guess, than I thought it would originally.
>
> Participant 7, end of case study 1

On the whole, then, there is evidence that some (but not all) participants gained a more nuanced understanding of the relationship between these commonly-cited barriers to using FEA in the design process.

6.3.5 Importance of Effective Communication About FEA

At the beginning of the project, communication about FEA results was not heavily emphasized as topic in the FEA survey questions, but emerged as a clear theme in the participants' comments.

> One of the basic problems with engineering results is the ability to relate them to others who aren't fluent.
>
> Participant 2, beginning of case study 1

> I think just knowing something about the [FEA] model is a good start. When we get specs, for example, sometimes they come from an FEA model I know nothing about, and there doesn't seem to be a place where one could find that information.
>
> Participant 7, beginning of case study 1

> [It is important to] explain limitations of models (in units and terms relevant to engineers), explain assumptions and impact they have on results, explain why you believe the model (test cases or previous cases run). … [Problems have occurred] when there was not tight

> communication between engineer and analyst. For example the engineer did not stay on top of assumptions made in model and simplifications, and did not really understand the limitations of the model.
>
> Participant 9, beginning of case study 1

At the conclusion of the project, the participants collectively responded that communication about FEA results had gone well from their perspective. In the more elaborative comments, they referred to various factors that facilitated effective communication, such as co-location of the FEA analyst with the rest of the design team, effective presentation and documentation of the FEA results, and the open nature of communication about FEA on the project—which, as described in Section 5.5, had been intended to reflect Schön's (1983) Model II theory of action.

> [The FEA analyst was] just right down the hallway, and so it's very easy to keep a very close communication link going… If you've got somebody in another group… it makes it much harder to have daily contact to just go in and say, "How are things going? What are the issues?" So I'm a big proponent of what [the FEA analyst] is doing and particularly with the fact that it is located within our own project. … [The FEA analyst] being on the design team, co-located with everybody else, so that he can get with the electrical designers on how they're laying their boards out, he can get with other mechanical engineers and designers on other parts of the system. So, again, it's an integrated part of our team, it's integrated into our design processes.
>
> Participant 1, end of case study 1

> On this particular project, [the FEA analyst] has been extremely good at providing results. His presentations that he gave were in -- depth—you know, exactly how something performed at specific frequencies for specific tests. I thought that in this case, it was extremely well-documented. … I've seen other cases where I just, you know—I see a couple results pages, and they're great, and… they don't mean anything to me.
>
> Participant 5, end of case study 1

> I think the way the FEA results were presented was sufficient for most people. And I work as a mechanical engineer kind of much more closely on this project, and I feel like if I wanted to really delve into the details—I didn't at this point—but if I wanted to, I could ask… and get all the kind of nitty-gritty models and things. I never felt like he was hiding anything from us, I guess. That kind of was my concern in that [FEA] survey—is that things could be manipulated or hidden. And I think a very

> good job was done on this project of kind of just laying it out there, and if something's off, you know, you just kind of say, 'it's off,' and don't try to sweep it under the rug.
>
> Participant 7, end of case study 1

> I think, with his team, [the analyst] never tried to hype the FEA, or 'sell it' for more than what it was supposed to do.
>
> Participant 9, end of case study 1

6.3.6 Influence of Previous Encounters with FEA

Several participants in the study demonstrated a strong tendency to fixate on a previous encounter with FEA, which could be either a good or bad experience. Their expectations of FEA were largely informed by that previous, defining encounter, which then seemed to act as a lens through which the present implementation of FEA was viewed and judged.

For example, a major overall theme in the comments from Participant 1 was the goal of bringing FEA into the typical design and testing activities of product development. In the following excerpt, much of that 'vision' is related back to a previous, positive encounter with the use of FEA.

> ***I was involved with [FEA]… on a project many years*** ago where we were designing a very large containment system that was designed to go through actually an aircraft accident and a fuel fire and have the contents survive. ***And so that was where I got a really good, I think, view of how the FEA and the modeling and the testing all gets tied in together***… So that was really where I saw how good, I think, FEA could be, and how much of a benefit it could be to a program. ***And I'm hoping on our program here that we'll be able to do that same type of thing*** as [the research investigator] develops and improves the models for our [circuit] boards and our system.
>
> Participant 1, end of case study 1 (emphasis added)

A major theme in the comments from Participant 6 was the need for FEA analysts to establish their teams' confidence in FEA as a viable and valuable part of product development. Again, much of that opinion was drawn from a previous encounter with the use of FEA—but in this case, a negative one.

> ***From my previous experience***, you come into a few issues when you are looking at FEA. Either the program is running out of money, and they don't want any more analysis done—they only want actual testing done—or that

> an engineer who is performing FEA is taking too long, and no one cares about the results because the actual testing results have already come in. … ***What I saw on the previous program*** is that FEA results just came in way too late. The design was done, it was already in production, and now I saw this thermal analysis of my, you know, my design… it almost doesn't matter anymore… But ***this is also the reason why I think this is important for FEA engineers, is that they have to be able to establish this confidence in this analysis in programs***, because if they don't, all their work is practically wasted, right? Because you do something, you present it, people look at it, no comments, and you stop and you move on. So the model is never carried through. … You have no chance of improving your model because nobody cares.
>
> Participant 6, end of case study 1 (emphasis added)

Throughout the case study, Participant 9 emphasized the importance of having an 'alignment' of 'motivations' when using FEA—i.e., that the use of FEA should be driven by the actual needs of the product design and development effort, and not by any extrinsic factors. That view was based on a previous experience working with FEA in an area that was more research-focused.

> [In the past, FEA failed to benefit a project] when the complexity of the FEA was driven not by project/product needs, but by programmatic needs—dictating that FEA "must" be used, or that certain codes "must" be used, or that a certain number of elements "must" be used… to promote other programmatic objectives.
>
> Participant 9, beginning of case study 1

> Other times [that I've seen FEA used for vibration and shock modeling] were at a very much larger scale, with very complex modeling, tera-scale computing, and so forth. And so ***in those cases, that's where I observed the challenges where some of the funding would be coming from the R&D side***, that would talk about new and novel ways to model jointed bolts, and jointed behavior, or material properties. ***So funding stream was coming from being very research-focused, state-of-the-art driven, where the application was somebody who wanted to know, is their part going to break. … That's where I saw a lot of this battle between end users who wanted answers, versus the R&D and the funding push.*** … Ideally the best alignment comes when everyone has the same motivations, right? So, in our case, because our business is about product, the product takes the lead role, right? And then the tools are used to support judgments made about that.
>
> Participant 9, end of case study 1 (emphasis added)

6.3.7 Increased Openness to Using FEA on Future Projects

In the interviews near the conclusion of the project, several participants made comments indicating an overall increased openness to the use of FEA in future product design and development efforts. In each instance, the participants attributed this openness to their experience on this case study project.

> [In the future] I think I'll approach it as saying, we need budget for analysis for every project I do. So, it made a big impact. … You can't quantitatively say, "I can't use this," or, "I don't want to use it," or, "we don't have the budget." We have to make the budget for this. So it is extremely important to me.
>
> Participant 5, end of case study 1

> Originally, I thought this was kind of a lot of work to put into [the FEA], because we were getting kind of one thing out of it at the beginning. But I think of it more as a kind of proof-of-concept for this project now. I think we could definitely make more use of it in the future, and I think this kind of just shows that it can work for small things like this. So maybe, for this project, if taken kind of in an isolated sense, and we don't follow through with this—it's kind of like, well, we just kind of did it just to do it. But if we do use what we learned from here on the second project—Project 2—I think that will be very valuable.
>
> Participant 7, end of case study 1

> In terms of setting up a project, I would say if we have the resources to do FEA analysis, I would definitely recommend it for a similar project in the future… I know now to put it into the design process, even though I'm not the one doing it.
>
> Participant 8, end of case study 1

> Now I want to be in a role to promote more dialogue about integrating FEA in our products. So not necessarily to promote, 'You must use it,' but to really have these conversations about, 'When is it useful? How can we use it? What's it's benefit? What should we expect of our staff?'
>
> Participant 9, end of case study 1

Over the course of this case study, Participant 9 on numerous occasions (at least five) directly referred other engineers, especially newer staff, to the research investigator for guidance in determining whether FEA could help with specific issues on their design projects. Taken out of context, the high number of referrals could be construed as evidence that Participant 9 views FEA as the solution to all design questions. But in reality, this participant seems to have a very grounded view of FEA.

> I don't want to go to either extreme… I think there's some case that we don't need FEA and testing, others we do. So it's case by case… At one end [of those extremes], it would be, 'Oh, we need modeling and simulation on every project, or every product, we do.' And then the other extreme would be, 'Oh, it buys us nothing. We have to test anyhow, so why should I invest money in that?'
>
> Participant 9, end of case study 1

6.3.8 Conceiving of New Applications for FEA

Over the course of the case study, a few participants asked the research investigator about particular technical issues of concern to them, and whether or not FEA could be used to address those concerns. For example, Participant 4, after taking a class on the design of measurement systems, asked whether or not FEA is a good tool for selecting optimal vibration and shock measurement points in a system. Participant 5, after seeing the initial presentation on the FEA of the three design concepts for this project (Sections 6.2.2 and 6.2.3), approached the research investigator about using FEA to assess vibration and shock failure levels of the electronics module itself (shown in Figure 14 [d]). Participant 7, after learning that some large mechanical parts adjacent to the modified electronics assembly (shown in Figure 29 and Figure 30) required a design change that could affect the vibration and shock inputs to the electronics assembly, suggested using FEA to determine whether or not additional prototype testing was needed.

In each of these instances, the participant's idea for an application of FEA was related to, but not exactly the same as, the way FEA was applied by the research investigator. In this sense, these instances of participants conceiving of new applications for FEA are similar to Rogers' idea of 're-invention' of an innovation by an adopter, which he defines as "the degree to which an innovation is changed or modified by a user in the process of its adoption and implementation" (2003, p. 180).

> Instead of simply accepting or rejecting an innovation, potential adopters are on many occasions active participants in the adoption and diffusion process, struggling to give meaning to the new idea as the innovation is applied to their local context. … People who use an innovation shape it by giving it meaning as they learn by using the idea.
>
> (Rogers, 2003, p. 187-188)

The connection is significant, because Rogers goes on to cite evidence from decades of diffusion research that a higher degree of re-invention leads to both a faster rate of adoption for an innovation (2003, p. 183-184), and a higher degree of sustained used in the future (2003, p. 183-184, 429).

6.4 Discussion

This section presents a concluding discussion of the case study. Section 6.4.1 summarizes the case study findings and maps them back to the original research questions. Section 6.4.2 discusses several possible rival explanations for the case study findings. A more general discussion of the limitations of the research method was included in Section 5.8. The findings for this case study are further discussed in Chapters 8 and 9 in the context of the entire two-case research investigation.

6.4.1 Findings Mapped to Research Questions

This case study was conducted with the goal of answering the four guiding research questions identified in Section 1.4. The findings are summarized below in the framework of those questions.

RQ1. What are the product development team's perceptions of FEA? This case study revealed with surprising clarity that the design team's confidence in FEA must be earned, and should not be assumed to exist a priori. Participants most often attributed their increased confidence in FEA to seeing, firsthand, a validation of the FEA results with experimental test data. A second factor cited by some participants was having confidence in the person performing the FEA. The study also revealed the strong influence that previous encounters with FEA—whether good or bad—have in shaping the participants' expectations for FEA in the constraints of a real product development effort.

RQ2. How does FEA impact the team's design thinking? This study revealed that members of the product development team overwhelmingly viewed the use of FEA as a means to obtain design confidence, in particular regarding the selection of concept 1 over concepts 2 and 3. However, FEA was by no means the only source of this confidence; rather, design confidence was cited as stemming largely from the similarity of the design to its predecessor.

RQ3. How do the team's views change on common barriers to adoption? This study confirmed that time required to use FEA is a leading concern in the minds of the participants, and also revealed that this concern persists even after exposure to what most participants viewed as a relatively successful use of FEA in product development. Some design team members gained a more nuanced understanding of the relationship between commonly-cited barriers to using FEA in the design process, such as FEA accuracy, assumptions, and time required. The importance of effective communication about FEA within the product development team also emerged as a clear theme in the data.

RQ4. How likely is the product development team to carry use of FEA forward? Several, but not all, team members appear to have an increased openness to using FEA on future projects as a result of their experience on this project. Additionally, a few individuals conceived of their own potential applications of FEA, which is one indicator of 'adoption' of FEA in their design thinking process.

6.4.2 Rival Explanations

In order to strengthen case study research findings, and in particular as part of an examination of internal validity, both Yin (2009) and Eisenhardt (1989) recommend the consideration of rival explanations.

Several participants cited confidence in the person performing the FEA as an important factor for their overall confidence in FEA. In this case, the person performing the FEA was the research investigator. Several participants also indicated, not surprisingly, that much of their confidence in the modified electronics assembly stemmed from its similarity to the predecessor design. In this case, the research investigator had previously served as the design engineer on that predecessor design. This confluence of factors almost certainly increased the confidence that the rest of the product development team had in the person performing the FEA and, ultimately, the FEA itself. Additional cases that better isolate one or more of these factors would be beneficial for developing a better understanding of which, if any, are most important.

Concept 1 was favored over concepts 2 and 3 by the product development team for several reasons, as described earlier. FEA was essentially used as a 'second check' of the team's collective design intuition, in an effort to prevent a rush to the wrong design decision while providing confidence that the right decision had been made. This is a perfectly valid design practice and use of FEA, but should be kept in mind, as it essentially shaped the role of FEA on this particular design project.

In some instances, the case study data contained evidence of possible misconceptions on the part of the participants' of what questions the FEA was intended to answer. In general, the misconceptions revolved around the idea that the FEA was answering the question of whether or not the parts in the design would 'break' during vibration and shock testing. The FEA did provide some limited information for such assessments, and follow-on calculations could be done using the FEA results, so there is some truth in this understanding. But abbreviated statements about parts 'breaking' sounds much more like stress analysis—a different, more common type of FEA than the dynamic FEA performed in this case study. So it is possible that some of the more positive things that certain participants had to say about FEA was a result of them being under the illusion the FEA was confirming something it was not, or with more certainty or definitiveness than it actually was.

Another possibility with regard to some of the more positive things that were said about FEA—e.g., concerning accuracy, time required, communication about results, and openness to FEA in the future, etc.—is that participants were simply being supportive of the research investigator, who was a colleague and a full member of the product development team. The intent underlying the research design was to mitigate this potential bias in the data and findings by having other researchers conduct the interviews, giving participants the opportunity for honest reflection on their experiences.

6.4.3 Results of Member-Checking

A draft of this case study report was submitted to all participants for review, in order to solicit feedback on the appropriateness of the conclusions drawn by the research investigator. Each participant was provided a copy of the draft in which direct quotes from their survey and interview transcripts were highlighted in yellow, as well as any other statements pertaining to them, to ensure that they reviewed and agreed with the usage and interpretation of the case study data by the research investigator. Eight of the nine case study participants responded to the request for feedback, each of whom expressed concurrence with the findings presented, either verbally or in writing.

A few participants took the opportunity to offer more reflection on this research. One participant noted both the advantages and disadvantages of the participant-observer research method that was utilized.

> The fact that you were the original designer, part of the team, and running the FEA ***may tend to lead or mislead the***

> ***team's views.*** However, ***it would be difficult to have an independent person run the same tests and see if the same results occurred.*** I believe it takes too much expertise that is not generally available to be able to do what you did independently and be effective for a design team.
>
> (Participant 2, after reviewing draft case study report)

Another participant expressed strong support for the overall approach of embedding FEA activities more fully in product design and testing activities, and the resulting confidence in the FEA analyst that such an approach fosters in a product development team.

> I think it is very true and interesting that you pointed out that "confidence in the person performing the FEA is an important factor for their overall confidence in FEA". … ***It is extremely useful and important for the analyst to be involved in actual testing*** (and even drive testing parameters and instrumentation), as you did, to correlate results with the model. So you'd close the loop: design, model, test, results fed back to model; update design, model, … etc., until a point when the confidence in the model is so high that it becomes a tool for double checking, without second guessing. Rarely do we have the luxury of the control (i.e., money and time) to do so. Besides external factors, ***the analyst himself must take initiative in this process and be motivated in searching for improvements.*** That is rare as well. … The same goes with some electrical engineers who dedicate their time to Spice modeling and analysis without touching a [circuit] board in their career.
>
> (Participant 6, after reviewing draft case study report)

7 Case Study 2: Development of a New Design

> A central feature of design activity… is its reliance on generating fairly quickly… any one of what might well be a large range of satisfactory solutions rather than attempting to generate the one hypothetically optimum solution. … Such a recognizably 'designerly' way of proceeding is probably… a reflection of the nature of the design task and of the nature of the kinds of problems designers tackle. The designer is constrained to produce a practicable result within a specific time limit, whereas the scientist and scholar are both able, and often required, to suspend their judgements and decisions until more is known.
>
> Cross (2007, p. 23)

This chapter covers the second case study design project. Section 7.1 provides an overview of the design requirements and the participants in the case study, who were members of the product development team. Section 7.2 covers technical details of the design effort, including the design constraints and concept, FEA modeling approach and assumptions, physical prototype testing, and comparison of FEA results to the test data. Section 7.3 presents the main findings from the interview and field note data. Section 7.4 concludes with an overall discussion of the case study and findings.

7.1 Overview

This case study design project involved a team at Sandia National Laboratories that was tasked with designing and developing an entirely new electronics assembly. This section provides an overview of the project. Section 7.1.1 outlines the design task. Section 7.1.2

summarizes the makeup of the product development team and compares it to the Sandia product development community overall, using the Context Assessment data (Chapter 3). Section 7.1.3 presents the project timeline.

7.1.1 Design Requirements

The design task consisted of designing a new, self-powered electronics assembly that was required to fit in a pre-defined, relatively restrictive volume. The weight requirement for the design was a maximum of about 8 lb.

Two small electronics modules, shown in Figure 45, were required to be incorporated into the design of the new electronics assembly. These modules were relatively new but already in existence, having been developed by a separate design team. The size of each module was 3 inches long by 2 inches wide by 0.75 inches tall, each weighing about 0.3 lbm.

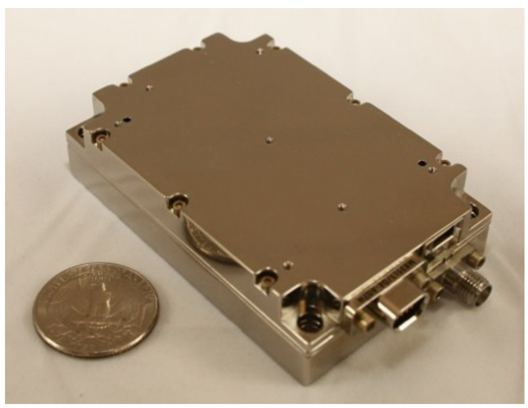


Figure 45: Existing electronics module required to be incorporated into the new design. The dimensions of the module were 3 inches long x 2 inches wide x 0.75 inches tall. The design was required to incorporate two of these modules.

The design required a custom, self-contained power source (i.e., battery), developed by a separate design team in parallel with the electronics assembly. The idea for the battery was to configure a certain number of commercial cells into an array. The required size and number of the cells were design variables that were driven by the voltage and capacity specifications for the battery, which were in turn driven by the demands of the electronics assembly and the two small electronics modules. Various concepts considered for the battery had estimated weights of around 4 to 5 lbm.

In addition to the inclusion of a battery and two small electronics modules, the new electronics assembly required sufficient circuit board area to incorporate all the circuits necessary to meet its electrical (functional) requirements. Early estimates from the electrical engineers on the team put a conservative goal for the total circuit board area at 125 in^2. Of that total, the goal was to have 30 in^2 in an enclosed volume sealed against electro-magnetic interference (EMI) noise, and the remaining 95 in^2 in an unenclosed volume.

Practical considerations such as overall manufacturability, sufficient space for electrical cable routing, and ease of assembly also factored heavily into the design goals. Thermal management was another recognized constraint, as both the battery and the two electronics modules were anticipated to generate significant amounts of heat during operation.

Finally, the design needed to be sufficiently rugged to meet its specified vibration and shock requirements. Since very little information existed on the vibration and shock failure levels of the various sub-components in the design (due to the newness of all required sub-components), the goal for the design was essentially to minimize the vibration and shock levels resulting from the internal response of the design. Generally speaking, this means ensuring that all housings, brackets, circuit boards, etc., are sufficiently rigid and well-supported that no destructive resonances occur in the frequency range of concern, typically below about 500 Hz. Finite element analysis was used during the design process to assess the leading design concept in this regard, as described in Section 7.2.

7.1.2 Product Development Team

The profiles of the case study product development team members are shown in Table 23 in terms of their technical backgrounds, length of time at Sandia, and present role(s) at Sandia.[14] Table 24 compares these team demographics to the Sandia product development community overall, using data from the Sandia Context Assessment (Chapter 3). Similarly, Table 25 summarizes the team's previous exposure to FEA and compares it to the Sandia CAS data. As these tables show, the product development team was reasonably representative of the larger Sandia population in terms of these metrics over the two-year period of the investigation. As previously mentioned, it should also be emphasized that the investigator was already experienced in the area of packaging design for ruggedized electronics, and was *not* simply an FEA analyst 'brought in' to implement the use of FEA for this case study.

[14] In addition, Participant 6 (from the first case study) was a member of the product development team for this project, but declined to participate in the second case study.

Table 23: Profiles of Case Study 2 product development team members.

Part. no.	Technical background	Time at Sandia	Self-described role(s)
1	Electrical eng.	≥ 26 years	Project / team leader
4	Electrical eng.	6 – 10 years	Electrical eng., Project / team leader
7	Mechanical eng.	≤ 5 years	Mechanical eng.
8	Business admin., Aerospace eng.	≤ 5 years	Program mgmt., Systems eng.
11	Electrical eng.	11 – 15 years	Dept. manager
12	Mechanical eng.	≤ 5 years	Systems eng.
13	Electrical eng.	≤ 5 years	Electrical eng.
Investigator	Mechanical eng.	6 – 10 years	Mechanical eng., FEA analyst

Table 24: Demographics of Case Study 2 participants compared to Sandia overall.
The team was reasonably representative of Sandia overall in terms of these demographic data.

Survey Question	CAS-pre		Case 2		CAS-post	
	No.	%	No.	%	No.	%
What is your technical background or degree field? (Select all that apply.)						
Electrical engineering	32	47.8	4	50.0	25	45.5
Mechanical engineering	26	38.8	3	37.5	23	41.8
Other	15	22.4	1	12.5	10	18.2
How long have you worked at Sandia (or your current employer)?						
≤ 5 years	16	23.9	4	50.0	18	32.7
6 - 10 years	13	19.4	2	25.0	8	14.5
11 - 15 years	11	16.4	1	12.5	9	16.4
16 - 25 years	8	11.9	0	0.0	10	18.2
≥ 26 years	19	28.4	1	12.5	10	18.2
Total	67	100.0	8	100.0	55	100.0
What is your present role at Sandia? (Select all that apply.)						
Department manager	6	9.0	2	25.0	8	14.5
Electrical engineer	17	25.4	3	37.5	16	29.1
Mechanical engineer	19	28.4	2	25.0	16	29.1
Project lead	16	23.9	4	50.0	18	32.7
Systems engineer	20	29.9	1	12.5	15	27.3
Other	13	19.4	2	25.0	8	14.5

Table 25: FEA exposure of Case Study 2 participants compared to Sandia overall.
The team was reasonably representative of Sandia overall in terms of their familiarity with FEA.

Survey Question	CAS-pre		Case 2		CAS-post	
	No.	%	No.	%	No.	%
Have you ever seen FEA used on your past projects?						
Yes	58	86.6	7	87.5	51	92.7
No	9	13.4	1	12.5	4	7.3
Total	67	100.0	8	100.0	55	100.0
Have you ever used FEA software?						
Yes	26	38.8	3	37.5	29	52.7
No	41	61.2	5	62.5	26	47.3
Total	67	100.0	8	100.0	55	100.0
Have you ever taken a course on FEA?						
Yes	21	31.3	3	37.5	22	40.0
No	46	68.7	5	62.5	33	60.0
Total	67	100.0	8	100.0	55	100.0

7.1.3 Project Timeline

The entire project was operated under a moderately tight schedule, with approximately 16 months devoted to concept generation and evaluation; detailed mechanical and electrical design; circuit board and mechanical hardware procurement; assembly of a partially-functional prototype; and vibration and shock testing. The case study timeline, with critical project steps and interview data collection points, is depicted graphically in Figure 46.

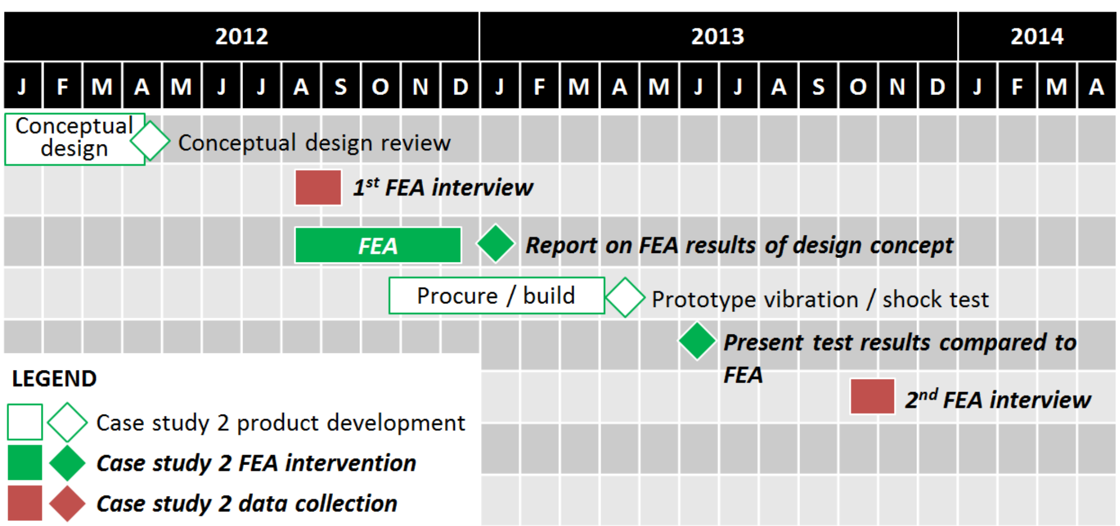


Figure 46: Case study 2 timeline.
Critical project steps and interview data collection points are shown.

7.2 Design, FEA, and Prototype Testing

This section describes the design, FEA modeling, and physical prototype testing that were performed as part of the product development effort. Elements of the intervention strategy are depicted in Figure 47 in contrast with the routine elements of the 'design-build-test' product development approach.

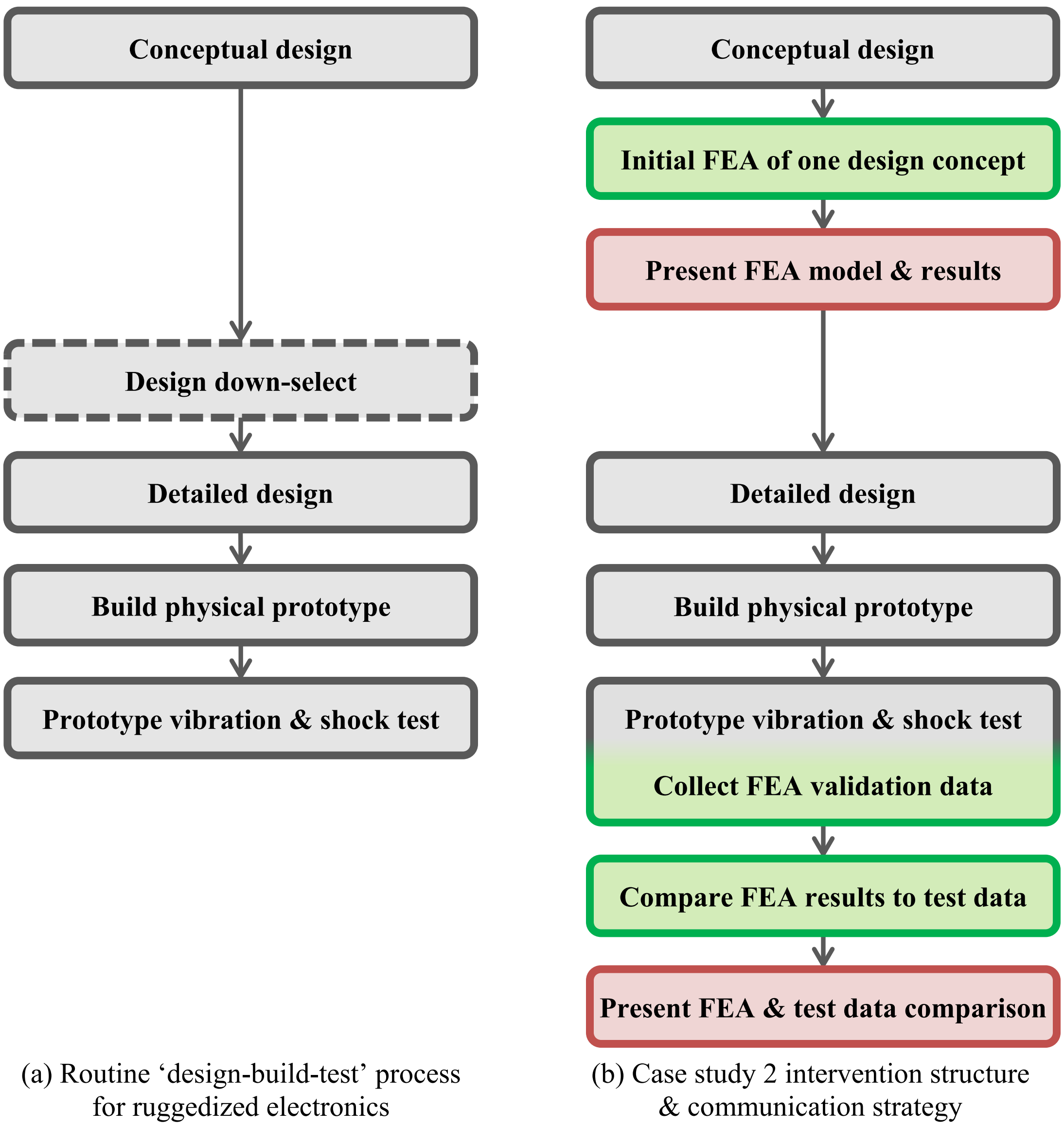


Figure 47: Case study 2 intervention structure and communication strategy.
(a) Routine steps in the 'design-build-test' product development process. Dashed outlines denote steps performed on an as-needed basis. (b) Steps involved in implementing FEA for vibration and shock analysis in case study 2 are shown in green with respect to the routine steps. Red boxes denote strategic points of communication about FEA to the product development team.

Section 7.2.1 presents the design concept that was generated. Section 7.2.2 provides an overview of the FEA model, and Section 7.2.3 presents the results of the FEA modeling. Section 7.2.4 summarizes the assembly and testing of a physical prototype. Finally, the experimental results are compared to the original FEA results in Section 7.2.5.

7.2.1 Design Concept

The baseline design concept shown in Figure 48 through Figure 50 was presented by the research investigator to several members of the product development team in April 2012. In this concept, the battery is located at the center of the design, with all other subcomponents mounted directly to it. Since a large portion of the overall volume and weight available for the electronics assembly had to be allocated to the battery, it was turned into the major structural element in the overall design.

The design has two main banks of circuit boards, each of which are attached directly to the battery housing. The first consists of three boards enclosed in a housing that straddles the two electronics modules. The other is at the opposite end of the electronics assembly and consists of four boards supported by a series of brackets. The two small electronics modules are also attached directly to the battery.

The total area of the enclosed circuit boards was about 35 in^2, exceeding the 30 in^2 design goal. But the total area of the unenclosed circuit boards was only about 66 in^2, far short of the 95 in^2 design goal. The electrical engineers on the design team accepted this shortfall, acknowledging that it was the best that could reasonably be achieved considering the restrictive overall volume requirement and the size of the battery pack needed.

Attaching the two small electronics modules directly to the battery was not necessarily ideal in terms of thermal management, since all three of these components were expected to generate large amounts of heat during operation. However, the intent was to demonstrate through thermal testing and the use of thermal FEA that self-heating was sufficiently accounted for in the design.[15]

[15] The thermal FEA modeling was completed by a different team and was not part of the present case study, but is described in Scott et al. (2013).

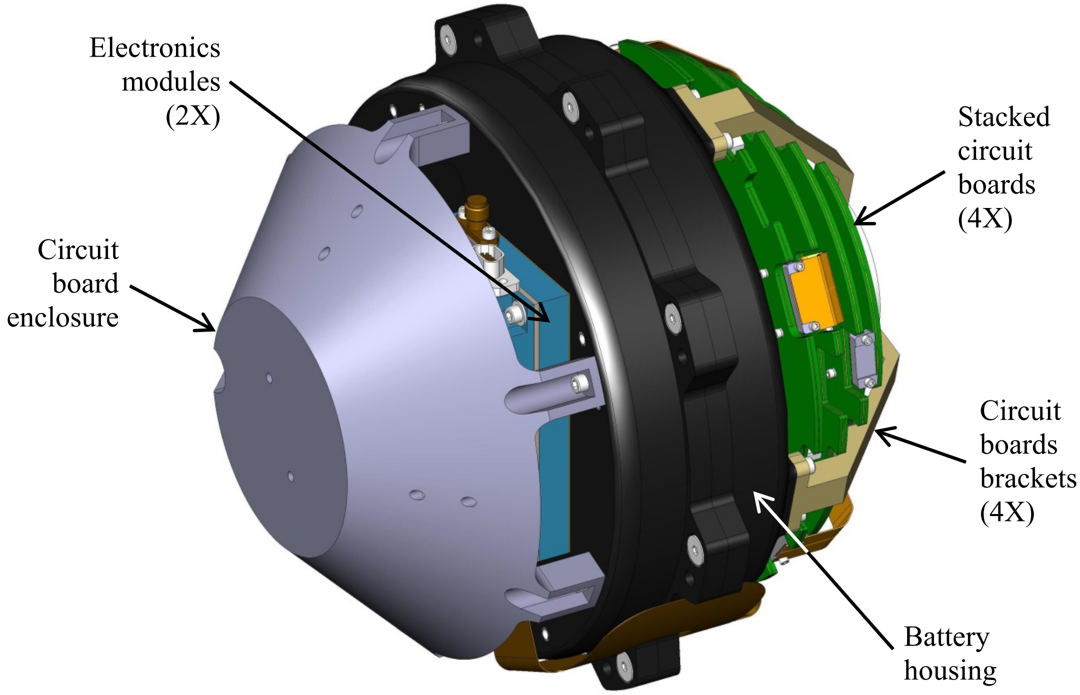


Figure 48: Design concept showing battery, electronics modules, and circuit boards.
The battery is the major structural element in the design, with all other required components directly attached to it. Electrical cables interconnecting the components are not shown in these views of the design model.

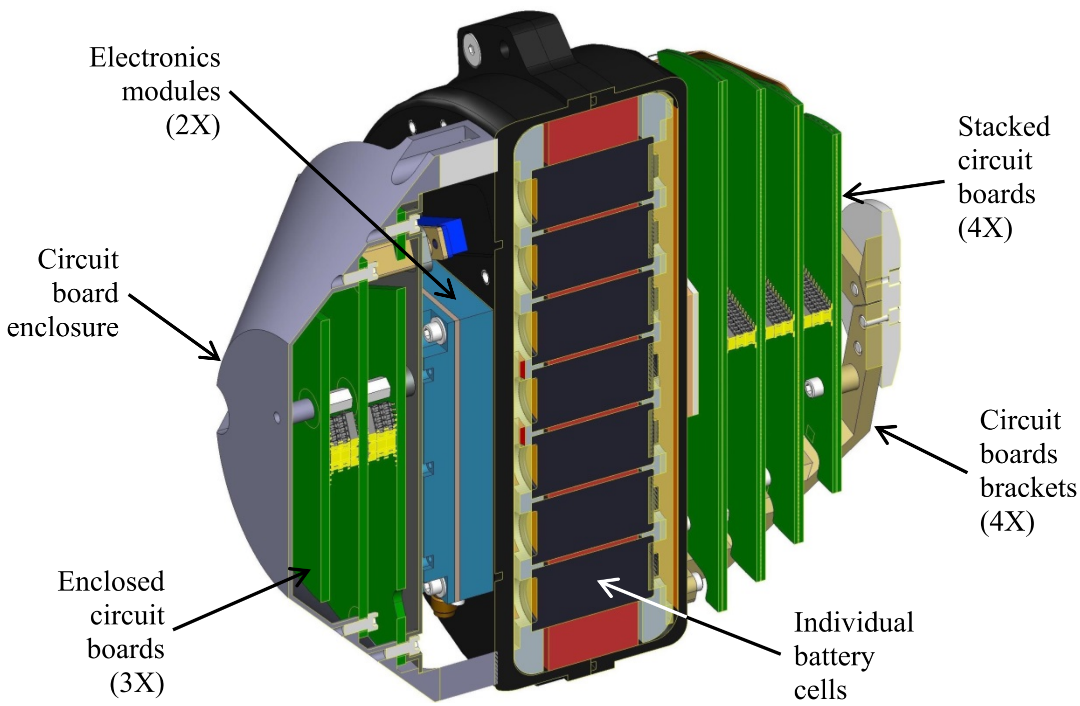
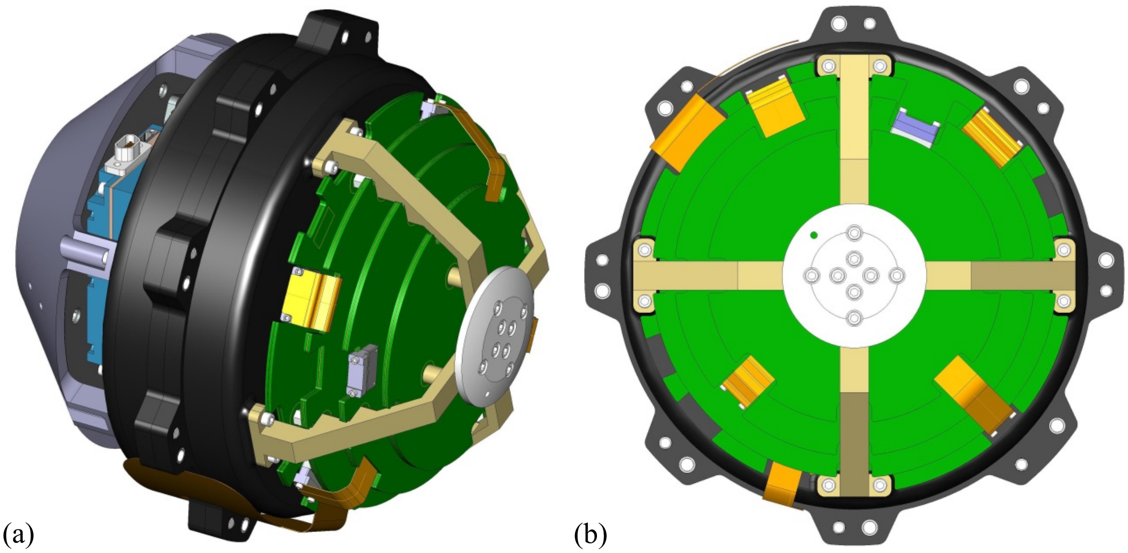


Figure 49: Cross-section revealing enclosed circuit boards and battery cells.
Three circuit boards are housed in an enclosure at one end of the assembly, and a bank of four stacked circuit boards is supported by brackets at the other end.



(a) (b)

Figure 50: Additional views of design concept.
(a) View showing stack of four circuit boards with support brackets. (b) End-on view showing eight mounting tabs around the perimeter of the battery housing for attachment to next-assembly.

Other design concepts were discussed, but only one was developed in detail. That concept used a different size and quantity of battery cells, resulting in a battery pack that had the same overall geometry but was slightly taller. However, due to time constraints on the product development effort and the overall complexity of the design and FEA model, only the baseline design concept shown was assessed using FEA.

7.2.2 FEA Model and Assumptions

Finite element analysis was used to predict the structural response of the design concept to the specified vibration and shock requirements. Specifically, the intent was to assess the response at critical points in the design to ensure that all housings, brackets, and circuit boards were sufficiently rigid and well-supported such that no destructive resonances would occur below about 500 Hz. The design models were developed using Pro/Engineer Wildfire 4, which is heavily utilized at Sandia for much of its design and product development. The FEA was conducted using Mechanica, the integrated FEA software available with Pro/Engineer.[16]

Generating the FEA models to conduct this analysis involved a variety of simplifications and assumptions, each of which is influenced by the specific purpose of the FEA models. Each presentation to the product development team of the FEA results (in January 2013 and again in June 2013) began with a brief reminder of these assumptions and limitations, which are

[16] Pro/Engineer Wildfire is now Creo Parametric, and Mechanica is now Creo Simulate. Both are made by Parametric Technology Corporation.

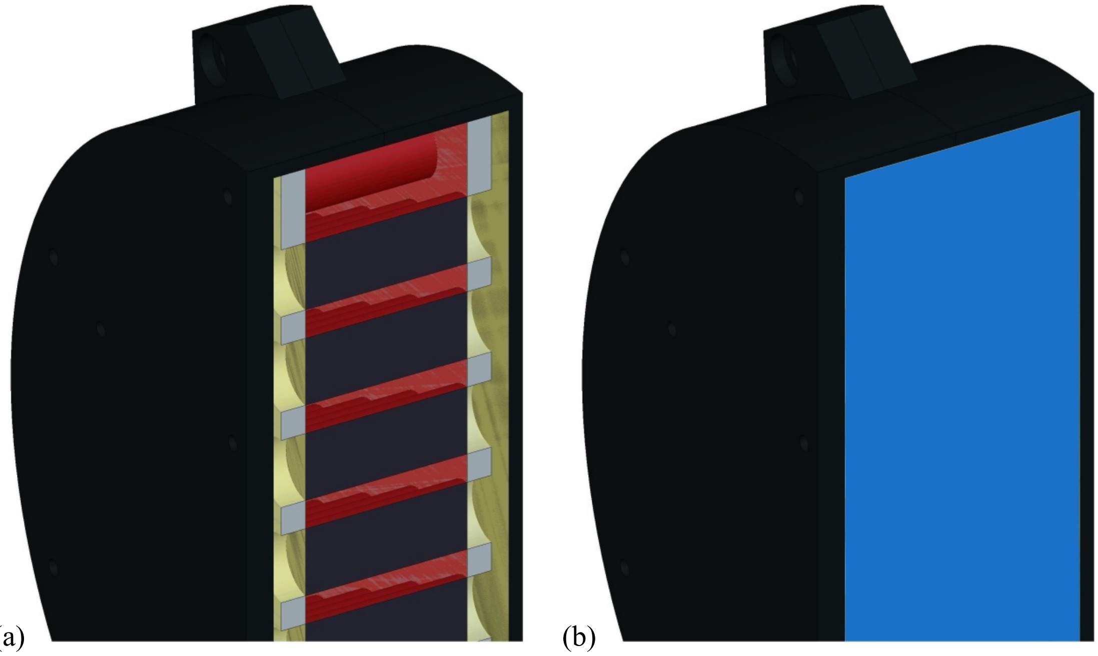
summarized below. Detailed information on the FEA model construction and the various assumptions involved is compiled in Appendix L.

Geometry. The goal with these models was to include sufficient detail to accurately model the *displacements* and *accelerations* of the parts in response to vibration and shock loading—but no more detail than necessary, in order to limit the amount of time needed for the models to run. This involved the removal of a variety of small, unnecessary features from the Pro/Engineer design model shown in Figure 48 through Figure 50 such as fillet radii, notches, holes, electrical components on the circuit boards, various mechanical fasteners and hardware, etc. This point is especially important, because mechanical FEA models are very often used to calculate *stress*, which requires more accurate geometric representation in the vicinity of the high stresses than is required to model displacements and accelerations.

Initial runs with the FEA model for shock inputs took substantially longer to run than expected. In an effort to reduce size of the FEA models, an alternate version of the model was developed for the shock analyses that used very simplified geometry for the battery pack internals. This alternate battery pack internal geometry is shown in Figure 51. This battery pack sub-model was developed under the assumption that capturing the first and second natural frequencies and mode shapes associated with the battery would provide sufficient fidelity to make the FEA results meaningful. External views of the resulting meshes are shown in Figure 52.

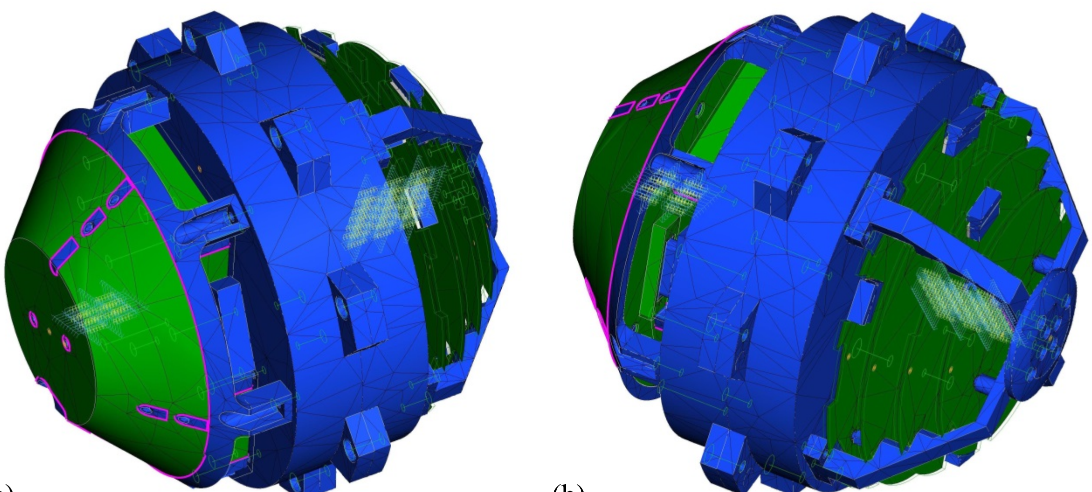
Element types. The FEA models were built using p-elements. The circuit boards were modeled using shell elements with bending (i.e., plates), as were the thin walls of the circuit board enclosure and the thin walls of the two small electronics modules. The remaining ‘bulky’ parts of the design were modeled using tetrahedral elements. This included the battery housing and internals, the legs of the circuit board enclosure, the support brackets for the bank of stacked circuit boards, and some (but not all) of the mounting hardware and fasteners, which is described more later.

Boundary conditions and loading. The models were constrained by ‘fixing’ the eight locations where the mounting tabs on the battery housing mate to next-assembly. The constraint was applied in all six degrees-of-freedom at the eight discrete locations of the screws used for attachment. The vibration and shock loads were applied to these discrete regions as specified accelerations.



(a) (b)

Figure 51: Comparison of detailed and simplified battery internal geometry.
(a) Detailed model used for vibration analyses included individual battery cells and simplified versions of all internal features. (b) Simplified model used for shock analyses used a solid mass to fill the battery internal volume, with the density selected to match the battery weight and Young's modulus selected to match the first natural frequency for the battery, as predicted using the detailed battery FEA model.



(a) (b)

Figure 52: P-element mesh used for vibration and shock analyses.
Solid (tetrahedral) elements are shown in blue and shell elements are shown in green. (a) View of circuit board enclosure. (b) View of four stacked circuit boards.

Connections. Many of the bolted joints in the design were modeled using Mechanica fastener elements. Generally, this method was used for the connections between the various pairs of adjacent metal parts, which included the following:

- the two halves of the battery housing,

- the legs of the circuit board enclosure and the battery housing,
- the four support brackets (for the stacked circuit boards) and the battery housing,
- the four support brackets and the 'cap' at the top of the brackets, and
- the two electronics modules and the battery housing.

The board-to-board electrical connectors in each bank of circuit boards were modeled using a combination of beam and spring elements. The beam elements were used to model the bending stiffness of the connectors, which are soldered to the circuit boards and impart a local stiffening effect to the boards. The spring elements were used to model the coupling effect that results from adjacent boards being 'plugged in' to each other.

A technique was required for modeling the connection formed between the standoff posts and screws used to secure the banks of circuit boards. Figure 53 shows the technique that was developed, which used a combination of 'bonded' and 'free' interfaces between adjacent, mated surfaces. This technique was estimated to give about the right amount of clamping effect to the circuit boards, without over-stiffening the joints. Similarly, a judicious combination of bonded and free interfaces between adjacent surfaces of the battery pack internal features, shown in Figure 51(a), was used to model the battery pack with the estimated correct amount of stiffness. Such approximations are important to note, because without extensive FEA modeling and experimental testing focused on these individual features in the design, they embody a series of assumptions that are incorporated in the FEA models.

Material properties. Linear-elastic material models were used for all components in the design. Linear-elastic is the simplest type of material model, requiring values for only Young's modulus and Poisson's ratio. For dynamic FEA models, the material density is also required. The linear-elastic approximation is somewhat crude for the non-metallic items in the design, such as the circuit boards, internal features of the battery design, and compressed thermal pads. It is a much better approximation for the metal parts, such as the battery housing, circuit board enclosure and support brackets, and housings for the electronics modules.

Damping. An initial damping value of 4% was used, based on limited historical data for similar, unpotted electronics assemblies. This value was believed to be a reasonable estimate for all of the design elements that attach to the battery—i.e., the circuit boards, support brackets, enclosure, and two small electronics modules. But the validity of this estimate for the design details of the battery itself was less certain, as the internals of the battery design were suspected to possibly contain a higher level of structural damping.

Measurement points. A variety of locations were selected for measuring the acceleration response of the design, several of which are shown in Figure 54. The intent of measuring accelerations was two-fold: (1) to use the responses at these locations for evaluating the design concept; and (2) later, during physical prototype testing, to place accelerometers at a subset of these locations to collect data for validating/improving the FEA model.

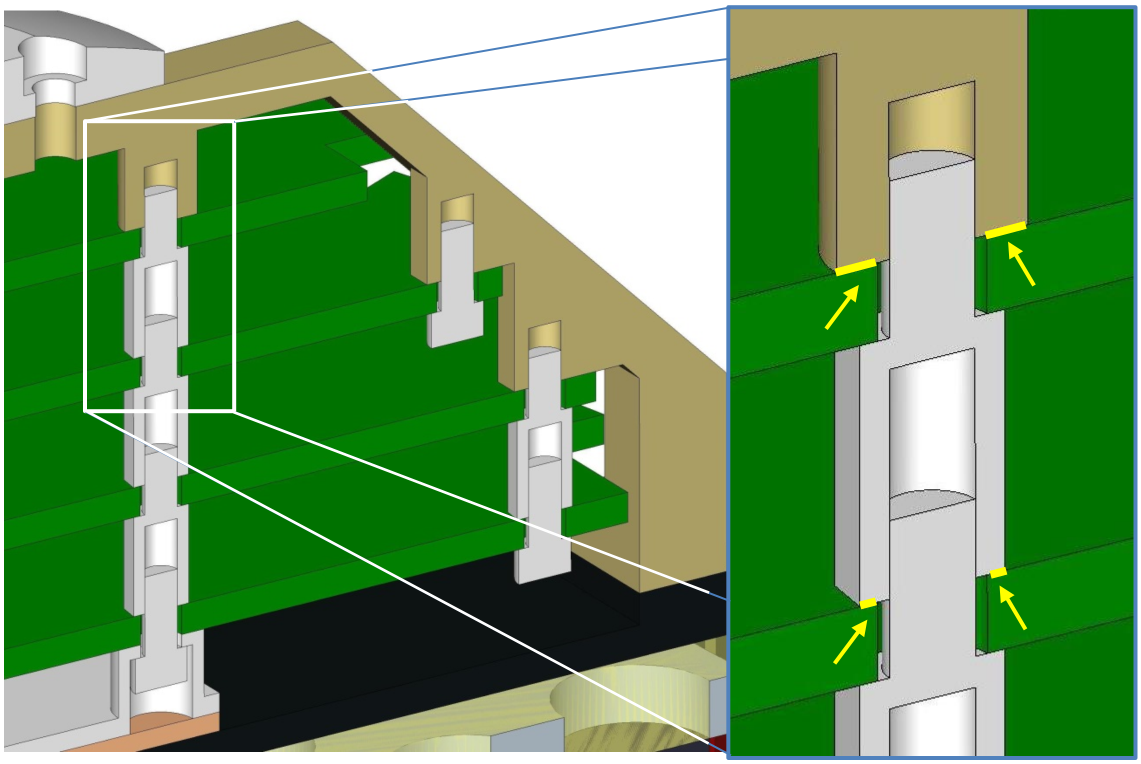


Figure 53: Method used to model hardware for securing circuit board stacks.
Free interfaces between adjacent parts are highlighted in yellow. Other mated surfaces in this view were 'bonded' together. This technique was estimated to give about the right amount of clamping effect to the circuit boards, without over-stiffening the joints.

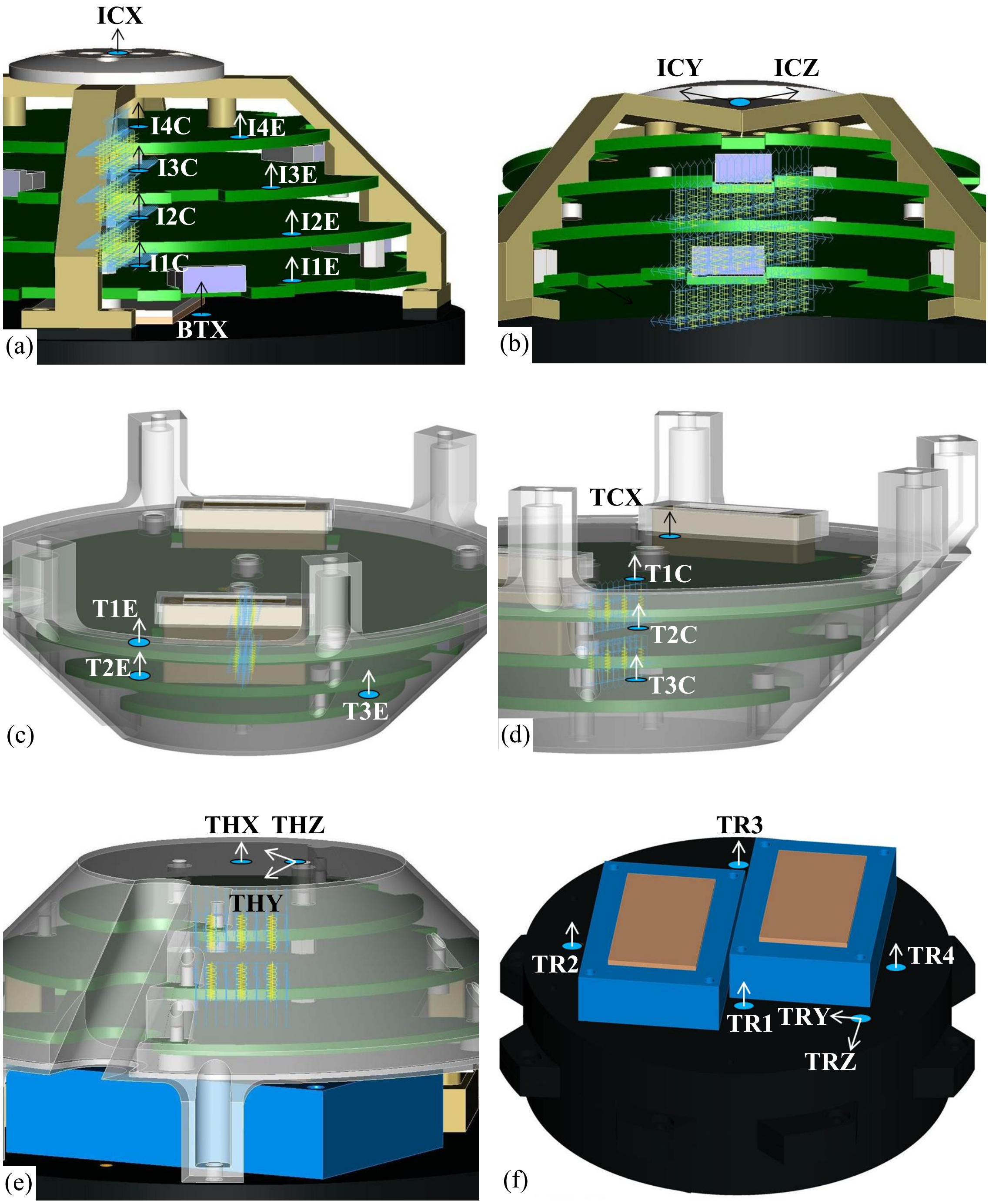


Figure 54: Response measurement locations.
(a)-(b) Center and edge of each stacked circuit board, top of the bracket cap, and the battery housing. (c-e) Center and edge of each enclosed circuit board, enclosure cover, and top of the enclosure housing. (f) Battery housing at several locations adjacent to the two electronics modules.

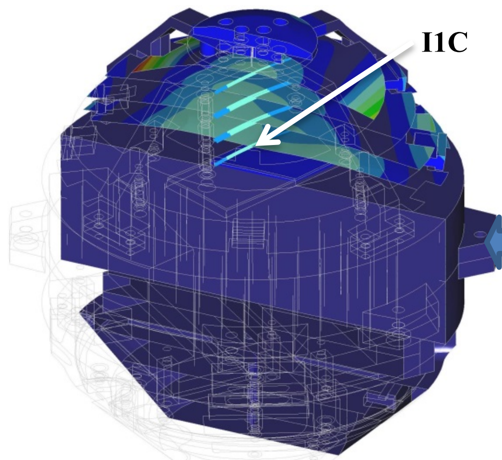
7.2.3 FEA Results

The FEA models were used to assess the response of the design to vibration and shock inputs. The results presented in this section are based on a report that was distributed by email to the product development team in January 2013. The response of the two banks of circuit boards were identified as the most important results, since severe resonances in the circuit board stacks would introduce a high risk of damaging the electronics, especially below about 500 Hz. Additionally, the response of the battery housing adjacent to the two electronics modules was closely monitored, in order to develop estimates for the vibration and shock levels that they would be exposed to in this new electronics assembly.

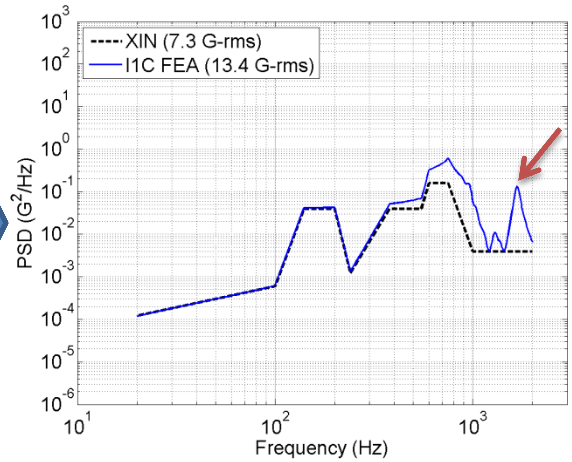
The emailed report was intended to introduce the team to the FEA models that were developed to assess the design concept, but the feedback received from the participants in response to this initial report was rather minimal. This may be a reflection of the fact that it occurred at a very busy point in the project for much of the team. In any case, with the benefit of hindsight, an in-person presentation would likely have been more effective at engaging the team's thinking and attention at this early point in the project, prior to prototype testing.

Vibration response of circuit board stack. Figure 55 shows several important mode shapes and natural frequencies associated with the response of the unenclosed circuit board stack, all of which were above the 500 Hz goal. Figure 55 also shows how these modes are visible in the vibration response at three important locations: the center of the largest circuit board, the edge of the largest circuit board, and the top of the stack in the lateral direction. As shown in Figure 55(a)-(b), the center of the board stack is not predicted to resonate severely in the normal direction, which generally can be an issue with stacked configurations. Since the largest circuit board has the largest unsupported span of any board in the stack, it has the potential for the lowest natural frequency and therefore the most severe resonance of its free edges. As shown in Figure 55(c)-(d), those unsupported edges do exhibit a somewhat severe resonance, comparable to that of the plug-in cards from Chapter 6.[17] In the lateral direction, the stack exhibits a moderate resonance that could be reduced by stiffening the brackets (i.e., making them bulkier), at the expense of a slight reduction of usable circuit board area.

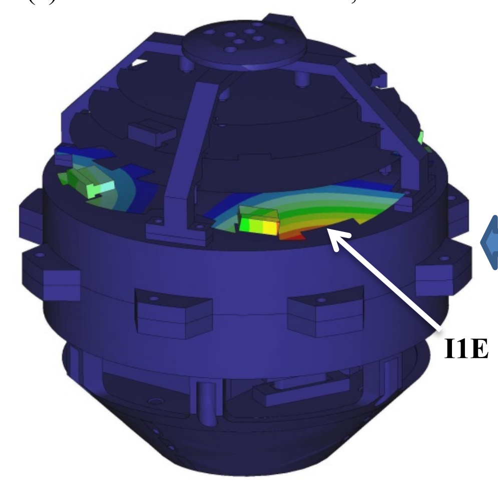
[17] The resonance shows a similar amount of amplification of the input environment as the plug-in cards from Case Study 1, but since the input is about one order of magnitude lower than the input to the plug-in cards, the peak is likewise about one order of magnitude lower.



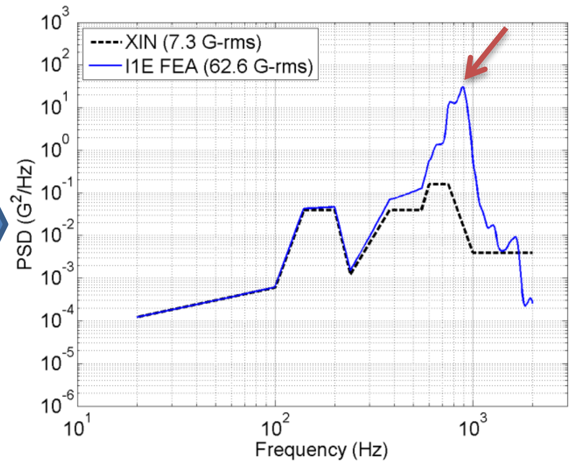
(a) Vertical motion of stack, 1639 Hz



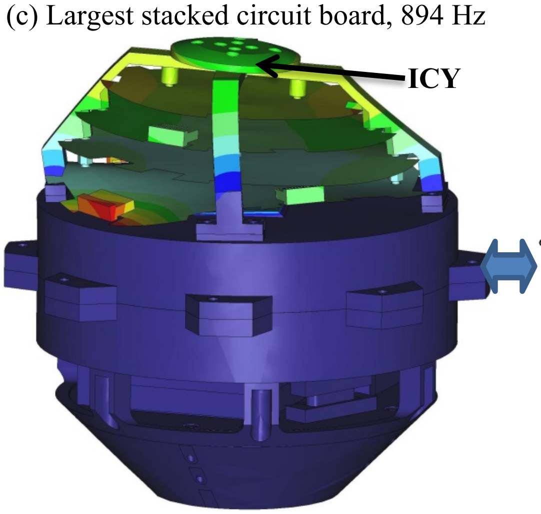
(b) Center of largest stacked circuit board



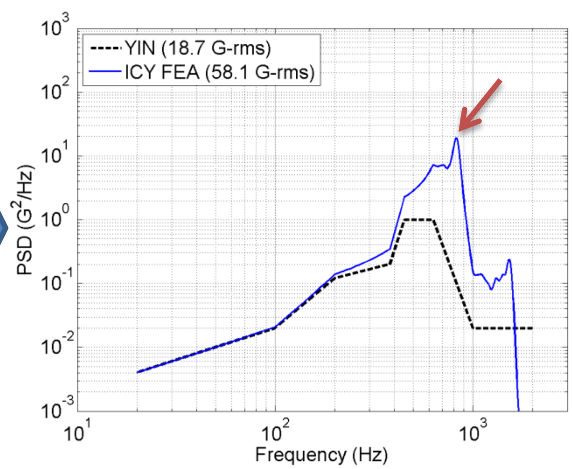
(c) Largest stacked circuit board, 894 Hz



(d) Edge of largest stacked circuit board



(e) Lateral motion of stack, 833 Hz



(f) Top of board stack, lateral direction

Figure 55: Important mode shapes and their effect on predicted vibration response.
(a)-(b) Center of largest stacked circuit board exhibited no severe resonance. (c)-(d) Edges of largest stacked circuit board exhibited a large resonance, comparable to that of the plug-in cards from Case Study 1 which had successfully passed vibration testing. (e)-(f) Lateral resonance of circuit board stack was moderate.

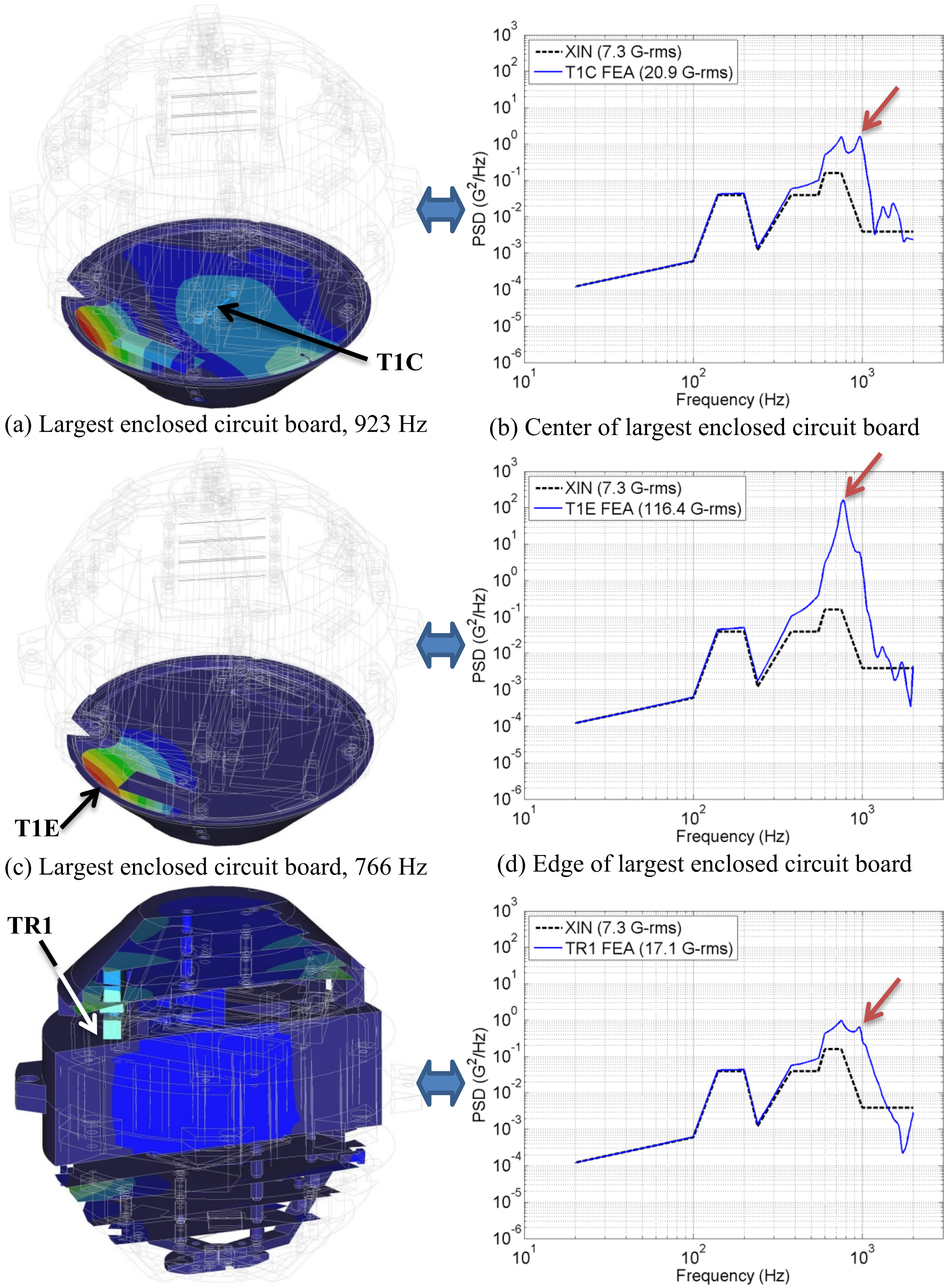
Vibration response of enclosed circuit boards. Figure 56 shows two important mode shapes and natural frequencies associated with the response of the largest enclosed circuit board, each of which was above the 500 Hz goal. Figure 56 also shows how these modes are visible in the vibration response at the center and edge of board. As shown in Figure 56(a)-(b), the center of the board is not predicted to resonate severely in the normal direction. Since this board has the largest unsupported span of any of the enclosed circuit boards, it has the potential for the lowest natural frequency and therefore the most severe resonance of its free edges. As shown in Figure 55(c)-(d), one of those unsupported edges does exhibit a somewhat severe resonance, comparable to that of the plug-in cards from Chapter 6.[18]

Vibration response at electronics modules. Figure 56(e) shows a mode associated with the response of the battery that in turn drives much of the vibration response at the electronics module, shown in Figure 56(f). Ideally, the design of the new electronics assembly would not amplify the input vibration levels at the electronics module. Realistically, some amplification is inevitable, and the amount predicted by the FEA was within reason. This predicted vibration response was in turn provided to the electronics module design team as an early estimate of the vibration specifications it would be required to meet.

Comparison of detailed and simplified battery sub-models. The simplified battery sub-model (Figure 51[b]) was used to predict the response of the electronics assembly to shock inputs, the results of which are presented in the remainder of this section. Figure 57 compares the first two modes associated with the simplified model to the corresponding modes associated with the detailed model (Figure 51[a]). The first two natural frequencies of the simplified model agree very well with those of the more detailed model (within 4 percent), and the corresponding mode shapes agree reasonably well.

Based on this comparison, the simplified battery sub-model was deemed to be a reasonable substitute in the larger FEA model over most of the frequency range of interest (20 Hz to 2 kHz). This assumption is valid for the results of the circuit board stack and the enclosed circuit boards, which are unlikely to be influenced by subtle differences in the response of the battery. The results measured directly on the battery housing, adjacent to the two electronics modules, are less certain.

[18] The resonance shows slightly more amplification of the input environment than the plug-in cards from Case Study 1, but since the input is about one order of magnitude lower than the input to the plug-in cards, the overall peak is roughly equivalent.

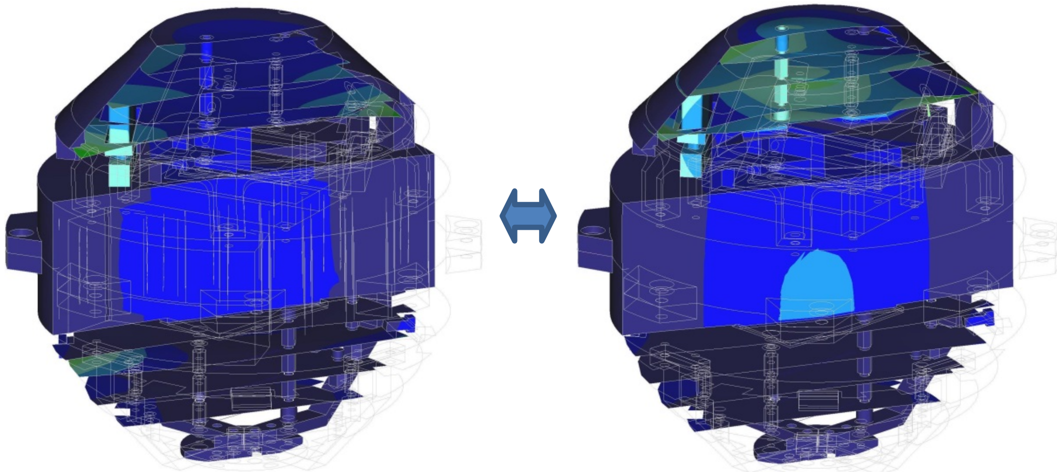


(a) Largest enclosed circuit board, 923 Hz (b) Center of largest enclosed circuit board

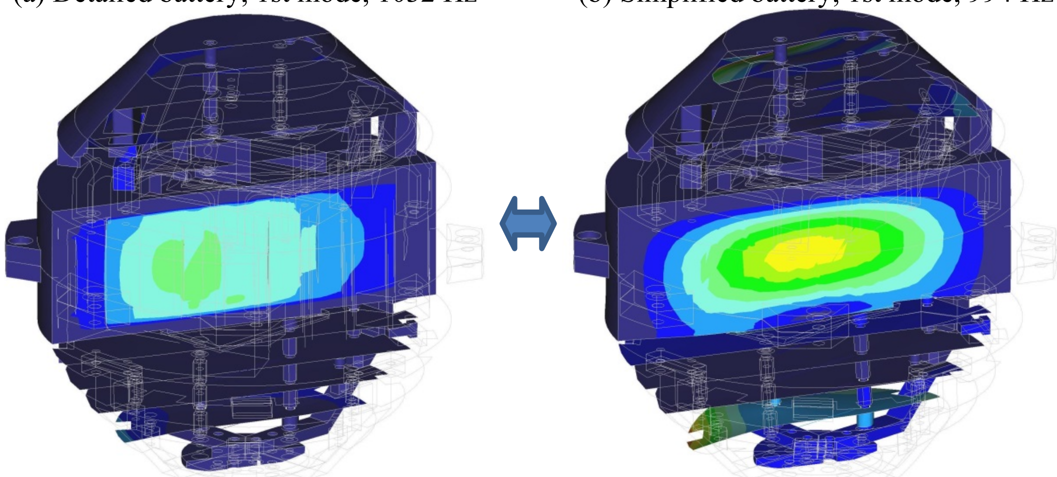
(c) Largest enclosed circuit board, 766 Hz (d) Edge of largest enclosed circuit board

(e) 1st mode of battery, 1032 Hz (f) Electronics modules

Figure 56: Important mode shapes and their effect on predicted vibration response.
(a)-(b) Center of largest enclosed circuit board exhibited no severe resonance. (c)-(d) Edge of largest enclosed circuit board exhibited a large resonance, comparable to that of the plug-in cards from Case Study 1 which had successfully passed vibration testing. (e)-(f) The response at the electronics modules was benign.



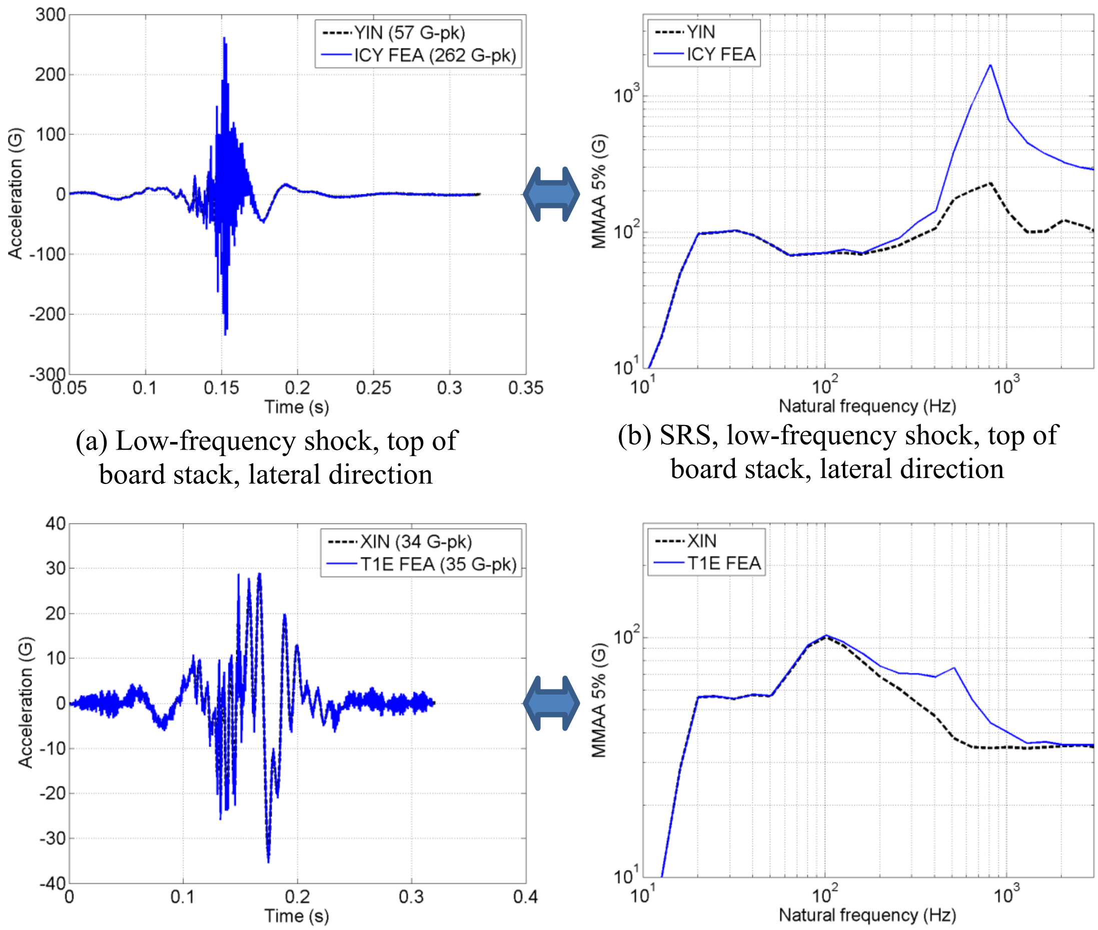
(a) Detailed battery, 1st mode, 1032 Hz (b) Simplified battery, 1st mode, 994 Hz



(c) Detailed battery, 2nd mode, 1429 Hz (d) Simplified battery, 2nd mode, 1448 Hz

Figure 57: Comparison of detailed and simplified battery sub-models.
The first two natural frequencies and mode shapes associated with the battery agree reasonably well between the detailed and simplified battery models. Based on this, the simplified battery model was deemed to be an adequate substitute in the larger FEA model over most of the frequency range of interest (20 Hz to 2 kHz).

Response to low-frequency shock. The majority of points monitored in the design did not show much amplification of the low-frequency shock input, which is a desirable design characteristic. Figure 58 shows the predicted response for two example locations. One notable exception was the lateral response of the top of the board stack, which amplified the input shock level by a factor of about five.



(a) Low-frequency shock, top of board stack, lateral direction

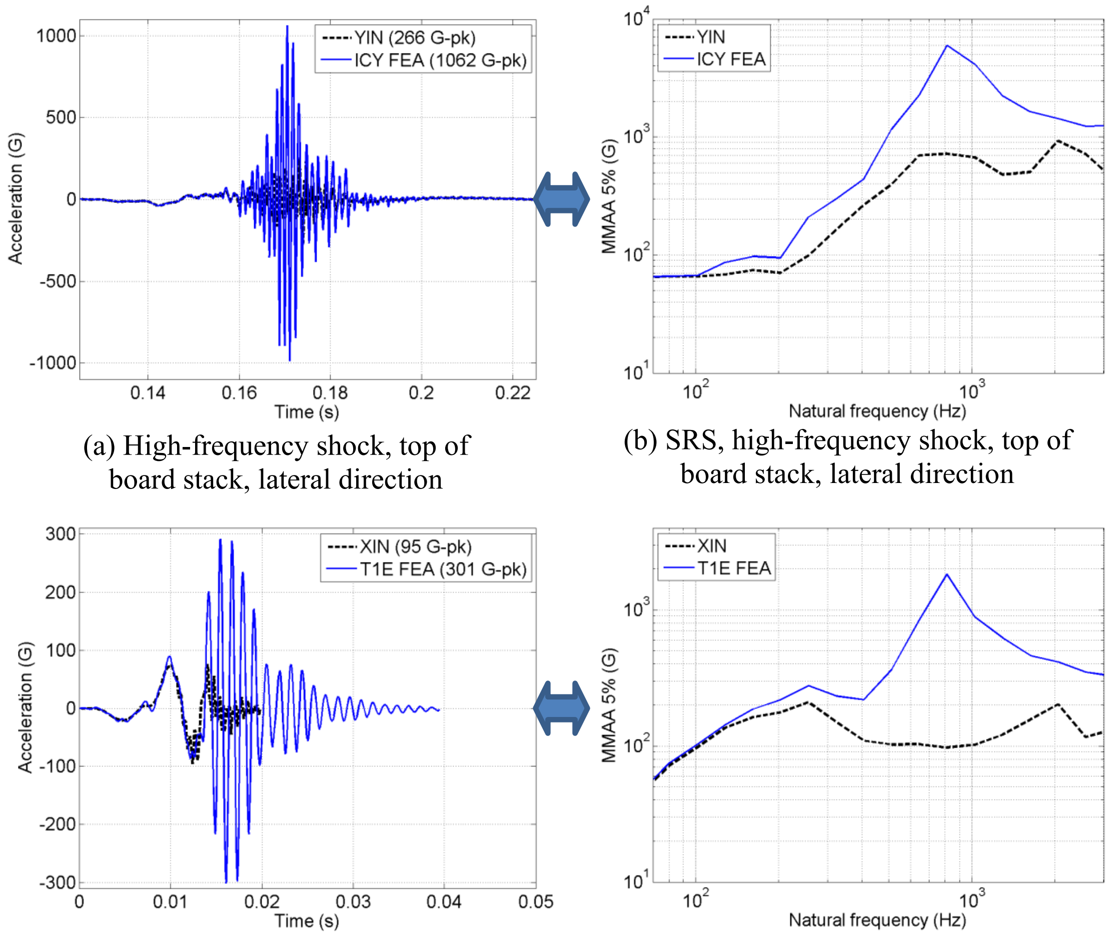
(b) SRS, low-frequency shock, top of board stack, lateral direction

(c) Low-frequency shock, edge of largest enclosed circuit board

(d) SRS, low-frequency shock, edge of largest enclosed circuit board

Figure 58: Predicted response to low-frequency shock input.
The majority of points monitored in the design did not show much amplification of the low-frequency shock input. (a)-(b) Lateral response of the unenclosed board stack exhibited the most significant amplification. (c)-(d) Edge of largest enclosed circuit board, which typified the points in the design where the response was minimal.

Response to high-frequency shock. Generally, the FEA model predicted a greater response to the high-frequency shock input than the low-frequency shock. Figure 59 shows the predicted response at the same two example locations as shown in Figure 58. All the unsupported edges of the circuit boards—both in the unenclosed stack and within the enclosure—exhibited amplification of the input shock level by a factor of about two to three. This type of amplification is not desirable but is difficult to prevent. The lateral responses of both the unenclosed board stack and the circuit board enclosure were also predicted to be significant, ranging from factors of about two to about four.



(a) High-frequency shock, top of board stack, lateral direction

(b) SRS, high-frequency shock, top of board stack, lateral direction

(c) High-frequency shock, edge of largest enclosed circuit board

(d) SRS, high-frequency shock, edge of largest enclosed circuit board

Figure 59: Predicted response to high-frequency shock input.
Generally, the FEA model predicted a greater response to the high-frequency shock than the low. (a)-(b) Lateral response of the unenclosed board stack. (c)-(d) Edge of largest enclosed circuit board, which typified the responses at the unsupported edges of all the circuit boards in the design. This type of amplification is not desirable but is difficult to prevent.

Time required to build and run FEA models. These FEA models took about four months at approximately 1/4 full-time-equivalency (i.e., the equivalent of about one calendar month full-time) to develop, de-bug, run, and pull together the results. The primary difficulty centered around modeling the internal details of the battery in such a way that Mechanica could reliably mesh and run the models without encountering errors. Once the models were successfully setup and debugged, running the modal analysis with the detailed battery model required about 3 CPU hours, and running three vibration profiles in each of three directions required about 45 CPU hours. In contrast, running the modal analysis with the simplified battery model required about an hour of CPU time, but running three shock profiles in each of three directions required over 550 CPU hours and about one week of calendar time.[19]

7.2.4 Laboratory Prototype Testing

A physical prototype of the design, shown in Figure 60, was procured and assembled into a test unit for laboratory testing in April 2013. The unit was a partially-functional prototype and included a combination of fully- and partially-functional circuit boards, shown in Figure 61 and Figure 62, and the two electronics modules, shown in Figure 63. The prototype was attached to a test fixture (also visible in Figure 63) and subjected to vibration and shock testing using an Unholtz-Dickie T2000 electro-dynamic shaker table.

During the assembly process, accelerometers were attached to the unit at multiple internal and external locations to collect data for validating the FEA model and for diagnosing any anomalous behavior in the structural response. Notable locations that were monitored included the circuit board stack (Figure 60 and Figure 61), the circuit board enclosure and boards (Figure 62 and Figure 63), and the battery housing adjacent to the base of the two electronics modules (Figure 63). A combination of Endevco 2250-AM1 and Endevco 2222C accelerometers were used, with the FEA results guiding the allocation of the higher-range 2222C accelerometers for locations where a larger response was expected.

[19] Mechanica does the majority of its calculations without taking advantage of multiple processors. For modal and random vibration analysis, total CPU time was typically about 10 to 20 percent more than total elapsed time. For time-history shock analysis, CPU and total elapsed time were essentially identical. In order to make this work feasible, three Mechanica licenses were used to run multiple analyses simultaneously, reducing the 550 CPU hours required for the full suite of shock analyses to about one week of calendar time.

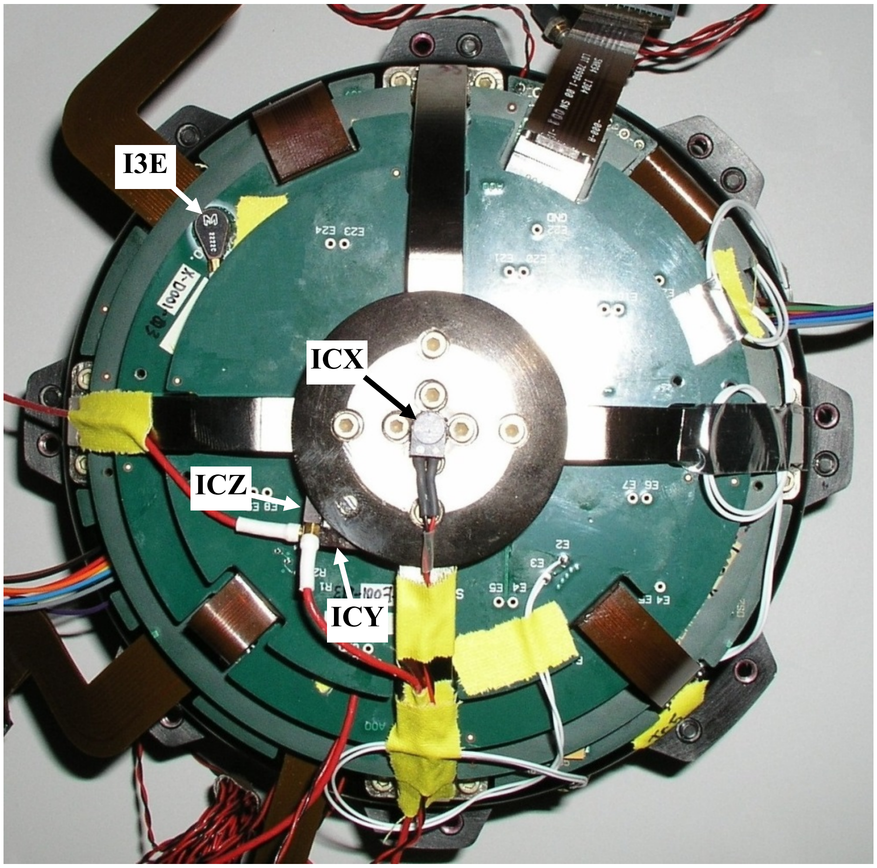


Figure 60: Partially-functional prototype of the electronics assembly.
Accelerometers were bonded to the unit at multiple locations to collect data for diagnosing unforeseen behavior in the structural response during vibration and shock testing, and for validating the FEA model. Three accelerometers at the top of the circuit board stack are shown (channels ICX, ICY, and ICZ).

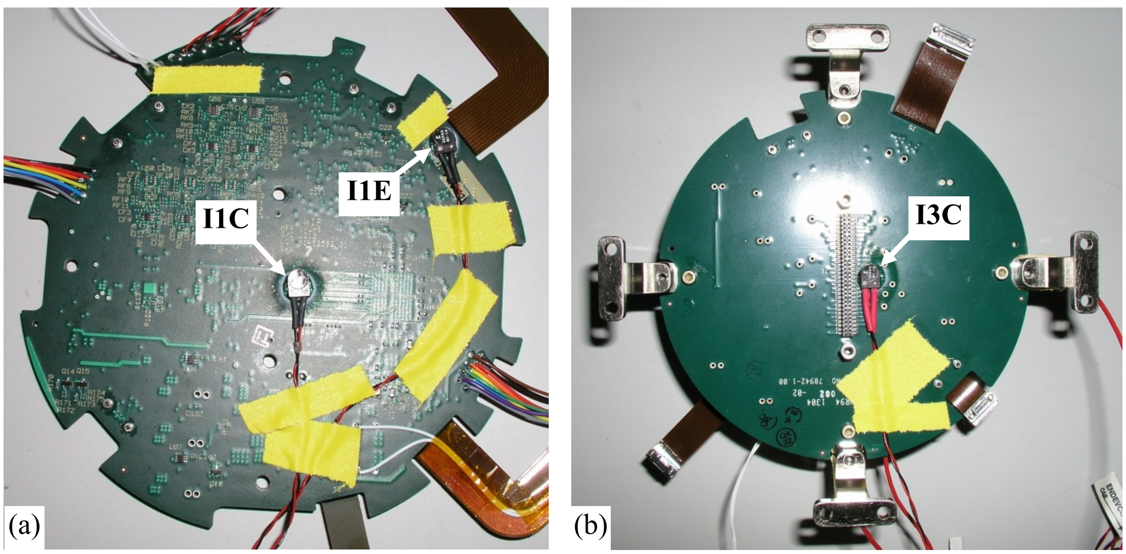


Figure 61: Prototype of the electronics assembly, showing circuit boards in the stack.
(a) First (largest) board in the stack with two accelerometers attached (channels I1C and I1E). (b) Third board in the stack with one accelerometer attached (channel I3C). A second is visible in Figure 60 (channel I3E).

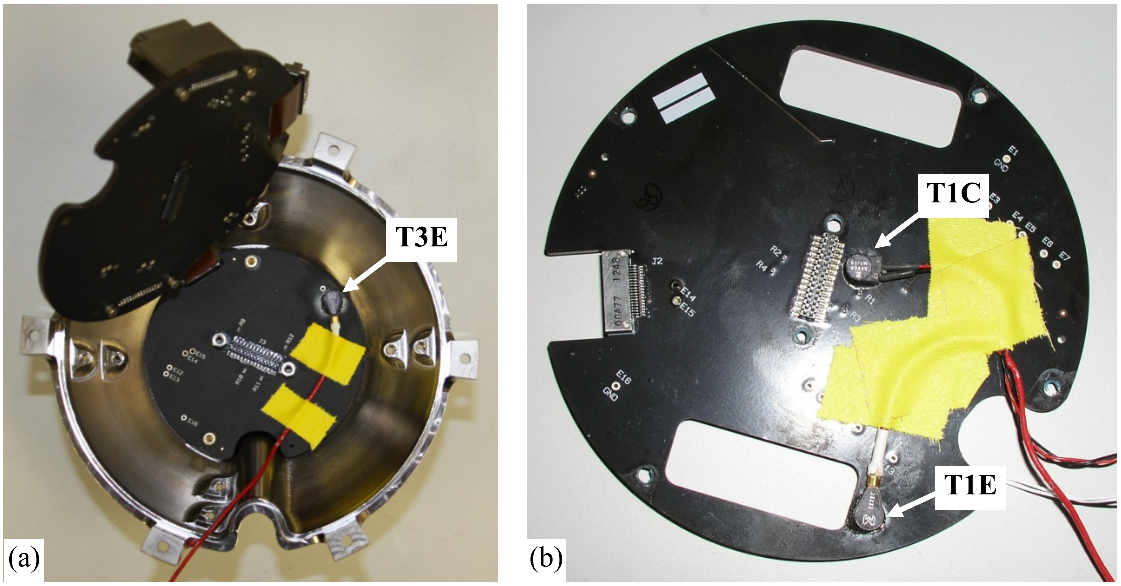


Figure 62: Prototype of the electronics assembly, showing the circuit board enclosure.
(a) Inside the circuit board enclosure, with the middle board folded out of the way to show the smallest board with one accelerometer attached (channel T3E). (b) The largest of the enclosed circuit boards, with two accelerometers attached (channels T1C and T1E).

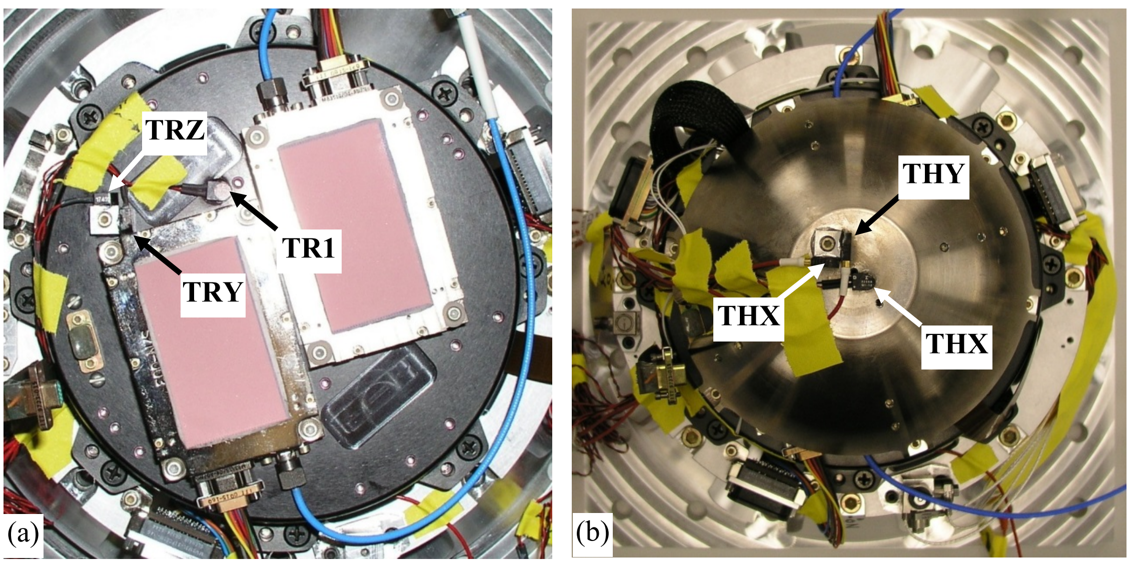


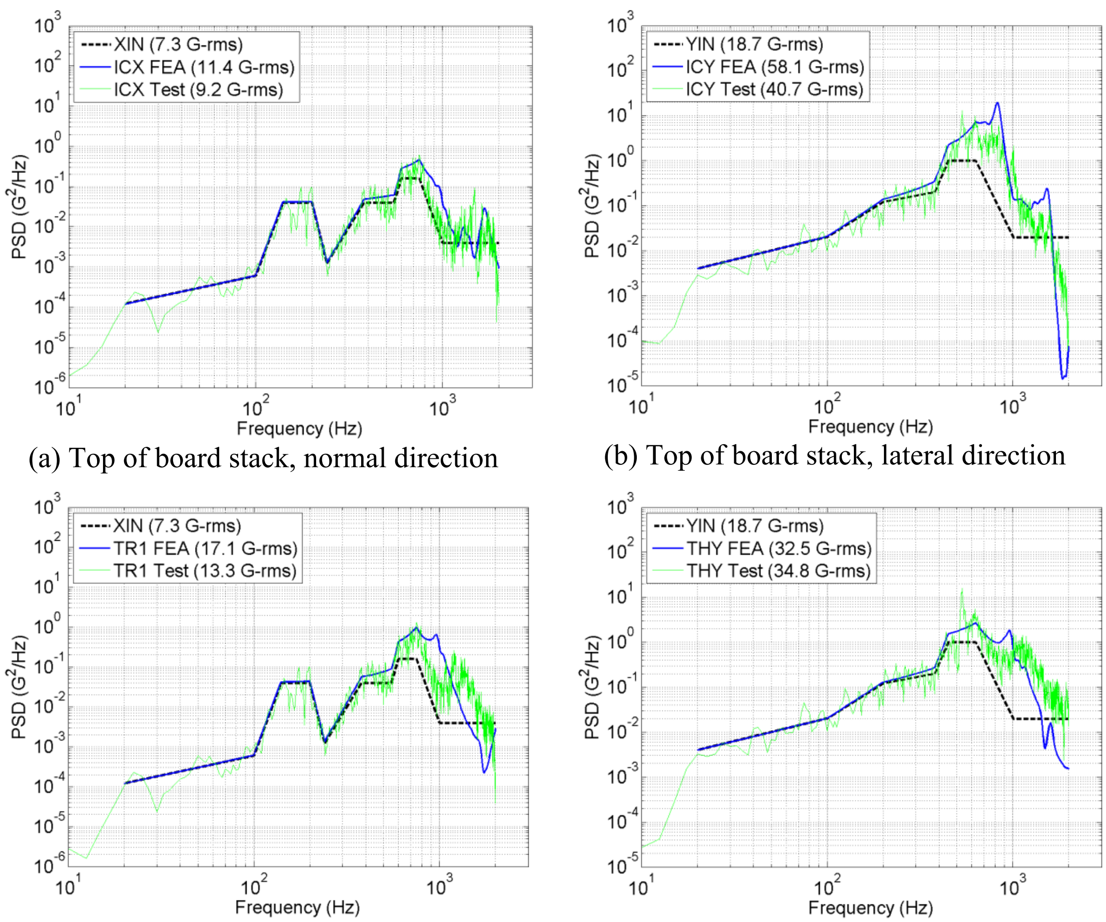
Figure 63: Prototype of the electronics assembly, attached to the test fixture.
(a) The circuit board enclosure is removed in this view to show the battery with two electronics modules attached. The response of the battery housing was monitored immediately adjacent to the base of the two electronics modules (channels TR1, TRY, and TRZ). (b) The assembled test unit, showing accelerometers on the top of the circuit board enclosure (channels THX, THY, and THZ). The unit was subjected to vibration and shock testing using an electro-dynamic shaker table (not shown).

7.2.5 Comparison of FEA to Test Results

The data collected during prototype testing was compared to the FEA predictions in order to explore the accuracy of the FEA model, better understand its limitations, and gain insights on how it might be improved. This section presents a summarized version of that comparison, with some reflection on the FEA model assumptions and overall modeling approach. The content is based on a presentation that was given in person by the research investigator to the other members of the product development team in June 2013. Overall, the presentation garnered much more substantial feedback from the participants than had the initial report that was distributed via email (Section 7.2.3). The majority of their questions and feedback focused on whether or not the observed resonances were severe—in particular, a resonance at edge of the smallest enclosed circuit board, which the FEA model failed to predict. Some participants also asked about the longer-than-expected run times for the FEA models. These and several other technical details regarding the comparison of the FEA predictions and test results are discussed below.

Element types (connections) for bolted joints. This modeling effort represented the most extensive use of Mechanica fastener elements to date by the research investigator. Overall, they seemed to perform well in terms of accurate displacement prediction for the main structural elements of the design—i.e., the battery housing, circuit board enclosure, and circuit board stack brackets—as shown in Figure 64. But for each fastener element used, Mechanica calculates a long list of values which are important for fine-tuning a model (e.g., if stress calculations are involved), but are less important for the dynamic analyses performed in this work in which accelerations are the quantity of interest. Mechanica calculates this list of values at every time step for the shock analyses, so one hypothesis is that the fastener elements were the cause of the long run times. This should be investigated prior to using them for future design efforts, as the run times for the shock analyses seemed excessively long and might be prohibitive, depending on the product development schedule and the determination of the FEA analyst.

Boundary conditions and geometry of the battery. Since the battery is the central structural element and heaviest part of the design, but has walls that are somewhat thin (the majority are only 0.100 inches thick), it was assumed from the beginning that its response would couple strongly into the overall response of the attached circuit boards—in other words, that the battery was a complicated boundary condition that could not be omitted from the scope of the FEA modeling. Indeed, some amplification of the input environment was observed in the test data measured on the battery housing, such as that visible in Figure 64(c). This confirms that, at a minimum, modeling the battery was important for predicting the vibration and shock levels imparted to the two electronics modules. It is less clear whether modeling the battery was necessary to accurately predict the vibration and shock response of the attached circuit board stack and circuit board enclosure, which opens up an interesting possibility for simplifying the model geometry in the future. Another possibility would be to investigate using the simplified battery sub-model for the vibration analyses, which may well produce sufficiently accurate results.



(a) Top of board stack, normal direction (b) Top of board stack, lateral direction

(c) Battery housing at electronics modules (d) Top of enclosure, lateral direction

Figure 64: Measured random vibration response at important structural elements.
Results shown for the original FEA model and the prototype test, which at most locations are well-correlated. (a) Response at the top of the circuit board brackets. (b) Lateral response at the top of the circuit board brackets. (c) Response on the battery housing, adjacent to the two electronics modules. (d) Lateral response at the top of the circuit board enclosure.

Material properties of polyimide circuit boards. The electrical engineers decided to fabricate the circuit boards in this electronics assembly using polyimide laminate, which was new to the design team and presented an unfamiliar set of material properties required for the dynamic analyses.[20] Table 26 shows the early estimates that were used for the FEA model, and Figure

[20] Historically, FR4 laminate material has been used for circuit board fabrication.

65 shows the responses measured at the largest stacked circuit board and the largest enclosed circuit board. Overall, the FEA model predictions match the test data reasonably well. Subsequently, a more thorough investigation was conducted of the commercial literature on polyimide laminate material, and a revised set of material properties was developed, also shown in Table 26. The reduction of Young's modulus combined with the increase of density would tend to shift the circuit board natural frequencies slightly lower, which may help the large resonances visible in Figure 65(b) and (d) better match the test data.

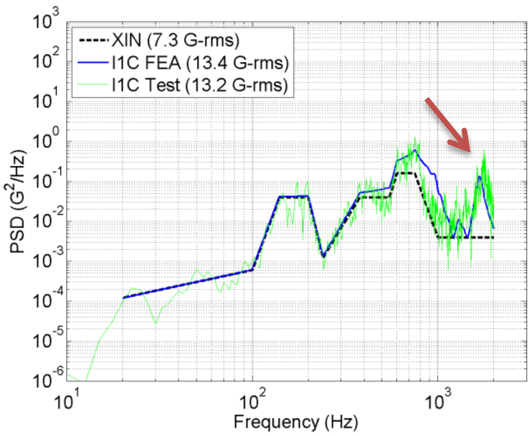
Table 26: Initial and revised estimates of polyimide circuit board material properties.

Effective bulk property	Initial estimate, used in FEA model	Revised estimate (for use in future models)
Young's modulus	4.0 x 10^6 psi	3.5 x 10^6 psi
Poisson's ratio	0.19	0.15
Density	0.080 lbm/in^3	0.089 lbm/in^3

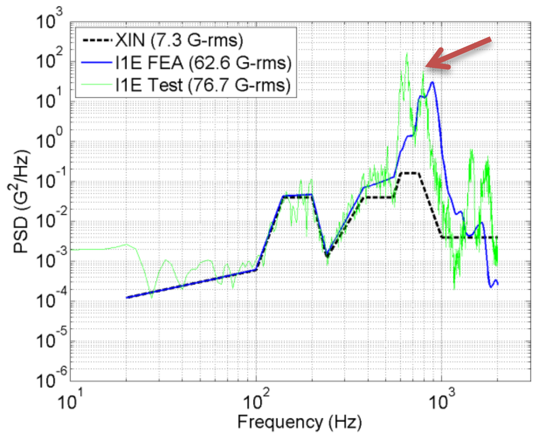
Modeling mechanical connections between circuit boards. The method used to model the mechanical hardware for securing circuit board stacks (Figure 53) was a new approach and seemed to provide reasonable accuracy, primarily evidenced by the overall accuracy of the circuit board responses (Figure 65). However, a more focused effort would be required to truly validate this technique.[21]

Damping. The estimate of 4 percent, which was based on historical data (including the results from Case Study 1 presented in Chapter 6), seemed to provide reasonable agreement between the FEA and test results. This is most evident in the large resonances at the edges of the two large circuit boards, visible in Figure 65(b) and (d), for which the amplitude of the FEA results match the test data quite well in terms of overall amplitude.

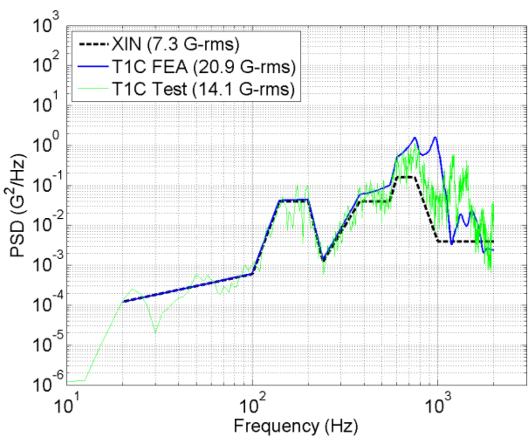
[21] The research investigator designed and conducted an experiment in 2010 with this as one of its purposes, but the experimental data were never analyzed in detail and the FEA sub-modeling was not performed.



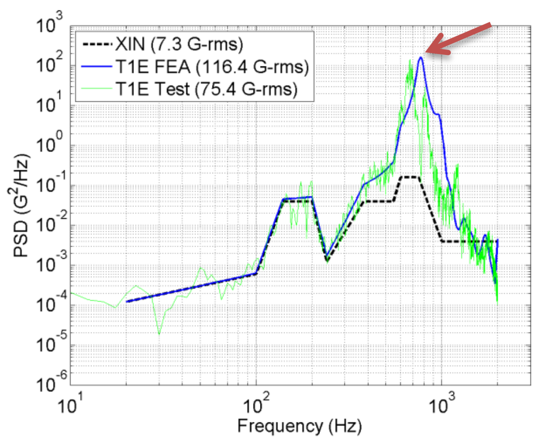
(a) Center of largest stacked circuit board



(b) Edge of largest stacked circuit board



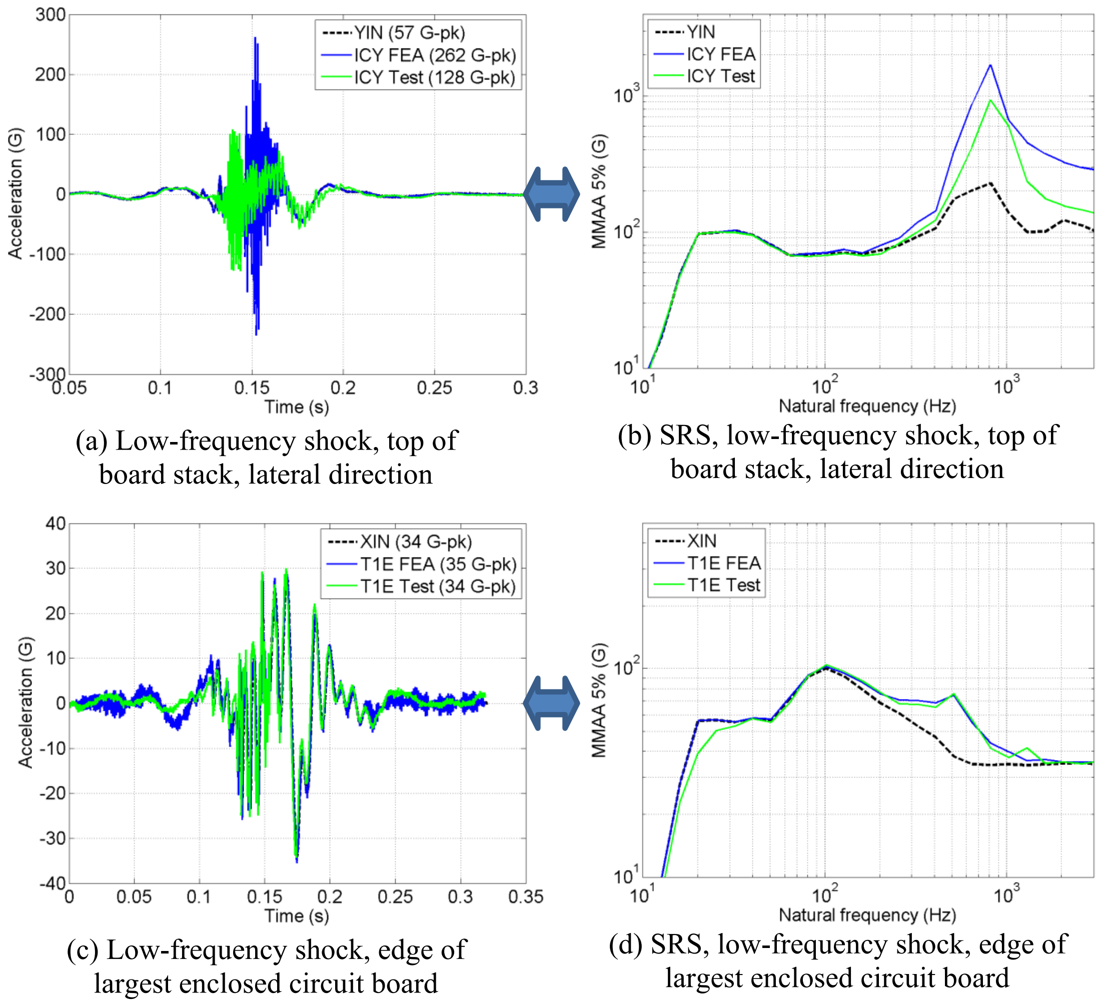
(c) Center of largest enclosed circuit board



(d) Edge of largest enclosed circuit board

Figure 65: Measured random vibration response of the two largest circuit boards.
Results shown for the original FEA model and the prototype test, which correlate well overall. At most locations, the dominant resonance of the circuit board is captured by the FEA model, as indicated by the red arrow. (a)-(b) Response at the center and edge, respectively, of the first (largest) stacked circuit board. (c)-(d) Response at the center and edge, respectively, of the first (largest) enclosed circuit board.

Response in shock environments. Example responses to low- and high-frequency shock inputs are shown in Figure 66 and Figure 67, respectively, at the same two example locations as shown in 7.2.3. Generally, for the low-frequency shock input, the FEA results tended to match the experimentally-measured values reasonably well. Two exceptions were the lateral responses at the tops of the board stack and the circuit board enclosure. At each of those locations, the FEA over-predicted the peak acceleration level by about 50 percent. On the other hand, for the high-frequency shock input, the FEA results matched the test data at only about half of the measurement locations, and tended to over-predict the results at the remaining locations. This reduced accuracy for the higher-frequency shock input is due to the diminished accuracy of the modal analysis results for higher natural frequencies and their associated mode shapes.



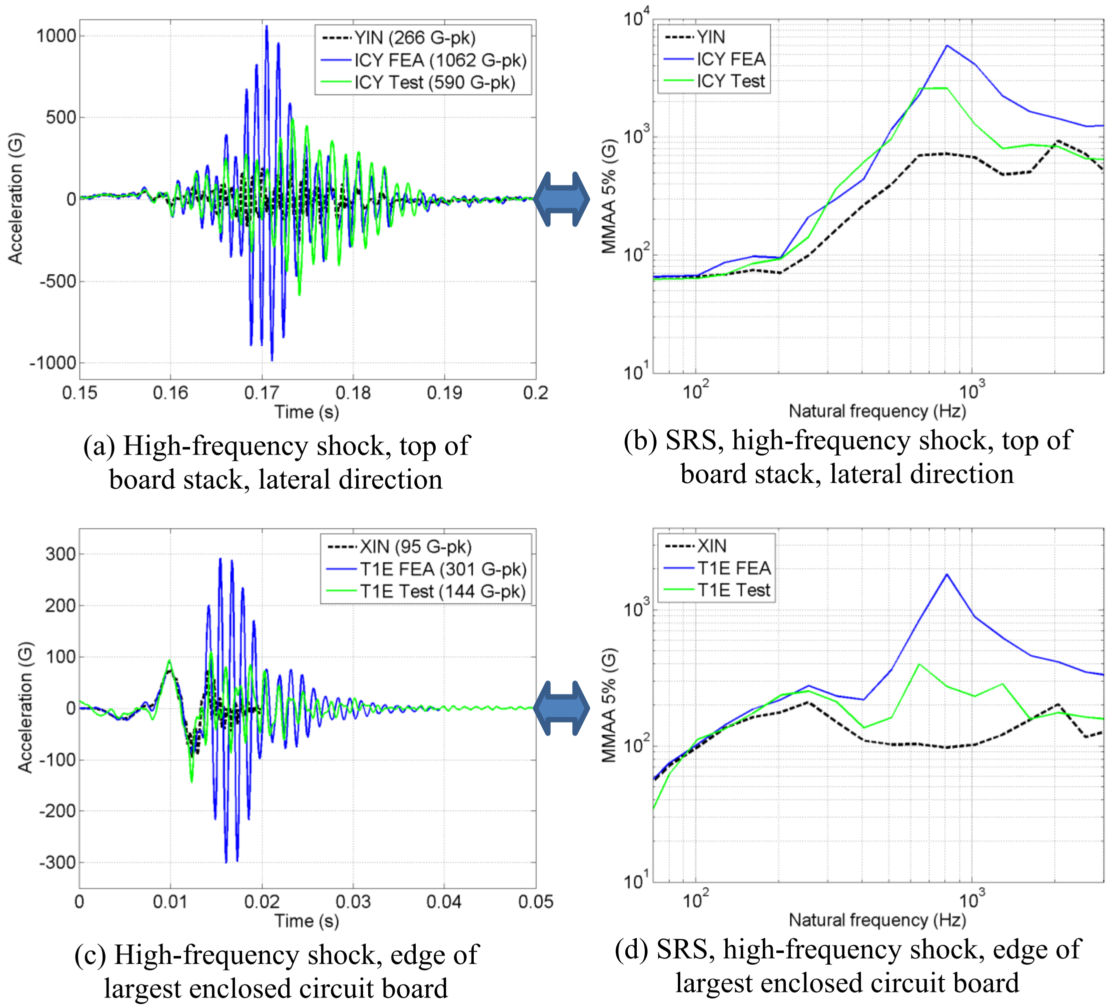
(a) Low-frequency shock, top of board stack, lateral direction

(b) SRS, low-frequency shock, top of board stack, lateral direction

(c) Low-frequency shock, edge of largest enclosed circuit board

(d) SRS, low-frequency shock, edge of largest enclosed circuit board

Figure 66: Measured response to low-frequency shock input.
Results shown for the original FEA model and the prototype test. Most of the points monitored in the design exhibited good correlation between the FEA results and experimental data. (a)-(b) Lateral response of the unenclosed board stack, which was over-predicted by the FEA model. (c)-(d) Edge of largest enclosed circuit board, which showed strong correlation between FEA and test results.



(a) High-frequency shock, top of board stack, lateral direction

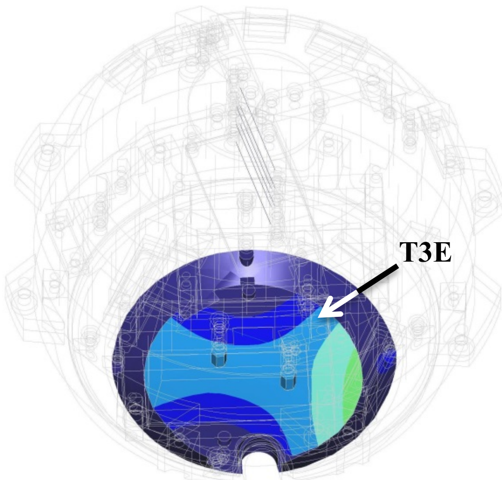
(b) SRS, high-frequency shock, top of board stack, lateral direction

(c) High-frequency shock, edge of largest enclosed circuit board

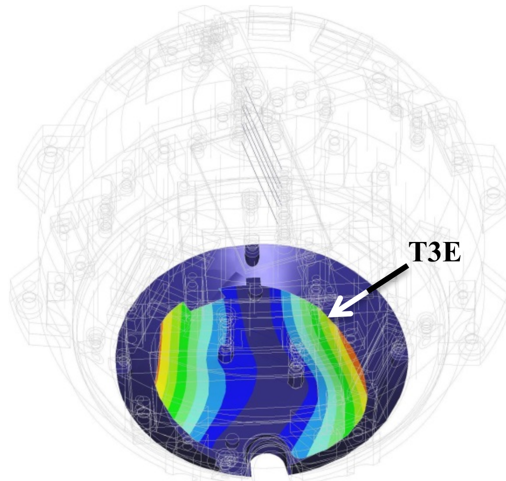
(d) SRS, high-frequency shock, edge of largest enclosed circuit board

Figure 67: Measured response to high-frequency shock input.
Results shown for the original FEA model and the prototype test. Generally, the FEA model either matched or over-predicted the response to high-frequency shock input. (a)-(b) Lateral response of the unenclosed board stack, which was over-predicted by the FEA model. (c)-(d) Edge of largest enclosed circuit board, which was also over-predicted by the FEA model.

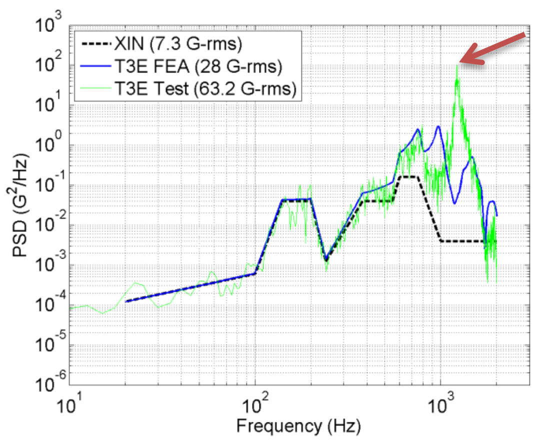
A notable exception to these trends was the response at the edge of the third enclosed circuit board, summarized in Figure 68. At this location, the FEA failed to capture a substantial resonance at about 1250 Hz. The FEA did predict resonances at nearby frequencies of about 920 and 1500 Hz, but they were not nearly as strong as that observed in the test data. This under-prediction of the response was uncharacteristic of the FEA, and identifying the cause(s) would require further investigation.



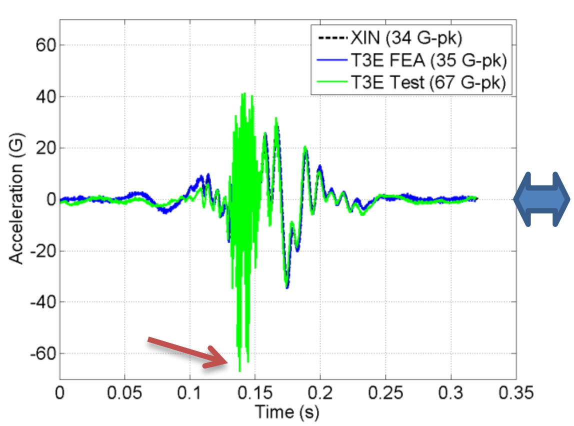
(a) Smallest enclosed circuit board, 923 Hz



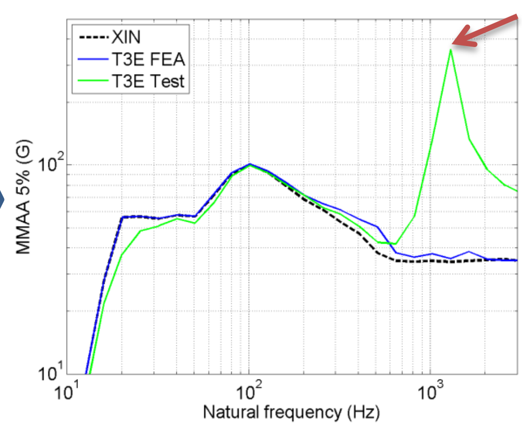
(b) Smallest enclosed circuit board, 1472 Hz



(c) Random vibration response, edge of smallest enclosed circuit board



(d) Low-frequency shock, edge of smallest enclosed circuit board



(e) SRS, low-frequency shock, edge of smallest enclosed circuit board

Figure 68: Measured response at the edge of the smallest enclosed circuit board.
This was the only instance—but a notable one—where the FEA failed to capture a large resonance in the design. (a)-(b) Predicted mode shapes at 923 Hz and 1472 Hz. (c) Random vibration response, showing the measured resonance at around 1250 Hz. (d)-(e) Response to low-frequency shock input.

7.3 Findings

The first and second FEA interview data, along with the investigator's case study field notes, were analyzed per the method described in Section 5.6. This section describes the main findings resulting from that analysis, with supporting case study data directly cited to help illustrate and support the findings.

Section 7.3.1 discusses the two main factors to which participants attributed their confidence in FEA—which were a direct comparison of FEA results to experimental data, and confidence in the person performing the FEA. Section 7.3.2 demonstrates how participants relied on multiple sources of design knowledge—including but not limited to the FEA results—to establish design confidence in their own minds. Section 7.3.3 describes how participants expected to see FEA have a more direct effect on product design decisions than was actually encountered. Section 7.3.4 discusses their concerns about the length of time that was required to run the FEA models on this project. Section 7.3.5 illustrates the importance of integrating the use of FEA and the FEA analyst into the design process. Section 7.3.6 discusses the participants' tendency to identify a 'model' implementation of FEA, and then frame and express their expectations relative to that model. Section 7.3.7 presents examples of the case study participants conceiving of possible applications for FEA on their own. Finally, Section 7.3.8 describes how although most participants expressed openness to the use of FEA in their future projects, nearly all attached some sort of caveat to their support.

7.3.1 Confidence in FEA Comes From Test Data and the FEA Analyst

As anticipated, the idea of 'confidence' was a significant theme in the data. Of the terms included in the word frequency chart shown in Figure 69, 'confidence' was the fifth most common overall, right after 'time' (and the much less surprising terms 'design,' 'FEA,' and 'testing').

Several ideas behind the term 'confidence' that had been uncovered in Case Study 1 (Chapter 6) were investigated in more detail. Regarding confidence *in FEA itself*, participants in the present case study typically attributed their confidence to one of two factors, the first of which was using experimental data obtained from physical prototype testing to validate the FEA results.

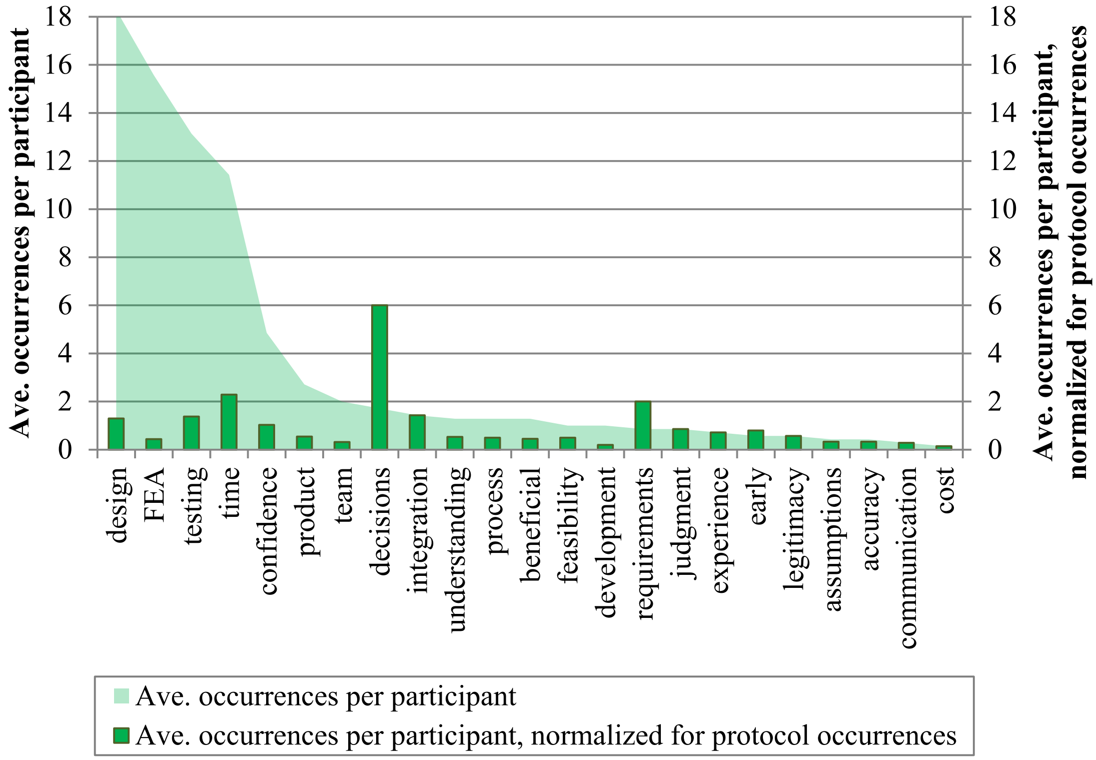


Figure 69: Case study 2 word counts, taken from 2nd interview transcripts.
Terms are sorted beginning with the most frequently-occurring on the left side of the chart. The word counts are also shown normalized for (i.e., as a ratio of) the number of occurrences in the interview protocol, as an indicator of topics that participants considered important. 'Time' was an anticipated theme, but its high occurrence in both the raw and normalized counts underscores its importance. 'Decisions' was a clear standout (but the only standout) in the normalized counts.

> I think, in the end, it has to be based on some test data. I think if you can show that, you know, your model at least predicts some result in some testing accurately, or within the accuracy that you need, then I think that opens up a lot of doors. But I think if you can't answer that question—if you can't show that that matches up at all—then I will lose a lot of confidence in your model.
>
> Participant 7, beginning of case study 2

> Once we had results, we wanted to put them against our model for validity and accuracy of the model, and I think… the advantage is we can now have more faith in the models moving forward, and in FEA in general.
>
> Participant 8, end of case study 2

> I'd say, overall, [confidence in FEA has] increased, just being able to see how well [the research investigator's] FEA models did match with our actual test data. It was pretty cool to actually see how he was able to kind of predict where the weak points would be and to what level they would respond to the different vibration environments. And so that was pretty cool to see, and it

> kind of opened my eyes to the power, or the value that FEA can have.
>
> Participant 13, end of case study 2

Related to this, a few participants noted the advantages of a design approach in which FEA and prototype testing are used in a complementary manner, leveraging the strength of each—rather than relying exclusively on one or the other.

> [FEA] gives you more information, it also allows you to help to sometimes scope your experiments or testing if you've got some information from FEA. And of course then the two of them are hopefully synergistic, and building on one another.
>
> Participant 1, end of case study 2

> Using FEA is a way to find information that you couldn't get any other way. So in that sense, you know, like I mentioned before, not being able to instrument every location on a circuit [board], or spend the time to go shake [vibration/shock test] every scenario—you know, you can rely on the FEA model. … So looking for ways to answer a question that you couldn't answer otherwise.
>
> Participant 4, end of case study 2

> One advantage was having the FEA model was able to show where possible weak points were in our design. And so then we were able to kind of instrument and pay close attention to those areas when we did our actual testing. And so that gave us, I think, the most useful data out of our testing, which is beneficial for the design as a whole because you're able to test at the weakest points, and if those perform well, then you know that the system as a whole will perform well. … I think, on its own, it would be a little dangerous to depend solely on an FEA approach to engineering. But if it's coupled with some actual testing or some, you know, other physical or kind of actual production engineering approaches, I think it can be very useful.
>
> Participant 13, end of case study 2

The other factor to which confidence in FEA was commonly attributed was an overall confidence *in the person* performing the analysis. Notably, some participants cited both factors simultaneously, as if to emphasize the equal importance of each.

> I think having confidence in your FEA results comes from testing and understanding your design, and I think, having the… the experience with your design to know how far to push your FEA model… A lot of it, I think, really depends on, then, the skill of the person that's doing

> the modeling, and how they apply that to the results of the testing.
>
> Participant 1, end of case study 2

> I think probably the person's experience using FEA [is important], and doing that kind of modeling. Clearly, they would still have to do a real test, and compare it to the model, and show me similar results. And I think between those two things, I would be pretty confident in using the model for future design… aspects.
>
> Participant 11, end of case study 2

> I think my confidence in [FEA] is based on the person who is doing the FEA analysis, not the analysis itself, because I've seen cases where the FEA can be wrong, but it's taken as the correct answer, or the correct method, and so, for me, it's really being able to trust the person who is doing the FEA analysis to make sure that it's a legitimate result.
>
> Participant 12, end of case study 2

> I think the fact that [the research investigator] was kind of involved heavily in both [design and analysis], it added confidence for me in his FEA model, because he knew the product very well, since he was designing it. So he knew, kind of, some of the nuances behind it that might factor in to how he built the FEA model.
>
> Participant 13, end of case study 2

7.3.2 Design Confidence Rooted in Multiple Sources of Design Knowledge

At the end of the project, participants were asked about the extent to which FEA influenced their design confidence. The results were mixed. Most participants indicated that FEA increased their confidence in the design, but several described other factors that were prerequisite to FEA supplying any additional confidence. The most common of these was experimental testing.

> I gain some confidence knowing we have a better model now, and we could solve future issues with this model that we have. But I don't know if it gave me any extra confidence when we went into this round of testing, necessarily. But it will give me confidence for future changes and future testing.
>
> Participant 7, end of case study 2

> [FEA] definitely influenced my confidence, because [the research investigator] did share his results side by side with the testing results.
>
> Participant 8, end of case study 2

> I think I looked at it more as a… well… a little bit, I mean. I relied more on the actual testing than the [FEA] model. But, it did help a little bit. … I think the fact that the results for the most part matched the model, or were very similar to the model—I think that did give confidence.
>
> Participant 11, end of case study 2

> [FEA] only confirmed [design confidence] after I looked at the test data. That's where I saw the comparison between the FEA results and the test, and that's where I felt very confident with the design.
>
> Participant 12, end of case study 2

> I think that having the FEA, or having FEA capability, provided us with a good amount of confidence in the design, at least on a qualitative level, which was I think very useful in shortening the design time and really developing a product that was, you know, very well designed right from the beginning, with our very first prototype.
>
> Participant 13, end of case study 2

One factor that was notably absent from this case study was design similarity. Three participants noted some similarity between this design and previous products, while the remaining participants did not. Regardless of their particular vantage point, the consensus view was that design similarity did not have a major impact on the team's design confidence.

> With Design Project [i.e., case study] No. 2, there was no similarity, other than… we could say there was similarity between this one and a completely separate project, but I'm not really looking at any information I've had with that other project as compared to this one. So this one is really looking at FEA analysis by itself, and comparing it to testing by itself, with no similarity to either Project [i.e., case study] No. 1, or really pretty much any other system that we have done before.
>
> Participant 1, end of case study 2

> We didn't have the luxury of using something that was… re-using a design, so this design was pretty new. So, um, I guess [design similarity] wasn't much of a factor.
>
> Participant 4, end of case study 2

> I mean, the design was a little similar to other designs, but not completely. So, yeah, I think we were a little confident going in, based on the previous design, but the FEA added even more confidence to that.
>
> Participant 11, end of case study 2

> For this project, it was a completely new mechanical design altogether. So it was very—there wasn't really much design similarity to go on. So I would say the amount of confidence gained from a similar design was negligible.
>
> Participant 13, end of case study 2

Speaking in more general terms, two participants discussed the idea that for products with a strong element of design similarity, FEA could be intelligently used to demonstrate conformance to requirements, rather than relying on prototype testing.

> The customers really want to see every little thing tested throughout the project life cycle, and every little component tested, whereas our timeline and budget really doesn't allow for that. And so we're trying to use FEA as a substitute to say, 'You know, [we've used] something similar before, and based on our modeling, what we're [using] now is better, and so we really don't want to test that piece.'
>
> Participant 8, end of case study 2

> [If] you know what the inputs are to the design, and you've seen the responses, and in a future project, if it's a similar input, and you're just improving on the design, you have a starting point. … If you were designing something new, but based on something else—you can always do that analysis on the existing one because you know it works right now. … And you can use that as your baseline to start.
>
> Participant 12, end of case study 2

Over the course of the case study, another participant came to the conclusion that FEA is most beneficial for brand new designs.

> If the design is a new design, I think that FEA can definitely be used to kind of focus your engineering effort to specific points of concern, and really strengthen your design as a whole, by kind of tackling those weak points.
>
> Participant 13, end of case study 2

Yet another participant repeatedly noted that the use of any simulation tool such as FEA must be combined with engineering judgment.

> It's not a panacea, it will not answer all of the questions, [but we should] understand its limitations and its advantages. … I'm a proponent of, well, any modeling and simulation, and, you know, with the caveats of you must have a rudimentary understanding of your system and

> what you're trying to model and simulate, so that you can then make a hopefully informed decision on the results that you get back from your modeling.
>
> Participant 1, beginning of case study 2

Collectively, the data illustrate how various sources of design knowledge—prototype testing, FEA, design similarity, and/or engineering judgment—are leveraged by the design team members in various combinations to establish design confidence in their own minds.

7.3.3 Visibility of Product Design Impacts is Critical

As shown in the word frequency chart (Figure 69), the term 'decisions' was a strong standout in the normalized word counts—nearly three times higher than 'time,' which had the second-highest value. Essentially, this is an indicator that participants were talking about 'decisions' in their interview responses much more than they were being asked about the topic. This insight provided by the word count data is backed up by the participant's comments, which reveal an overall view that FEA did not have any direct impact on product design decisions.

> So far, I think we have a good base, but we haven't actually done anything with it, other than to show that, oh, hey, our model matches our test results. … But hopefully in the future… we have design changes that can be evaluated using the model that we have. It hasn't come up yet in this project, so its usefulness hasn't really shown itself. … I think [using] the model to help with design decisions is coming, because I think there will be changes we'll have to make, that will kind of see how beneficial it is.
>
> Participant 7, end of case study 2

> I think it helped the team learn about FEA, and introduce the group as a whole to FEA and how the results can match the model, and therefore the model can help you. But, I'm still not 100 percent sure it actually drove any design decisions, so, in that sense, I'm not sure it helped the design aspect.
>
> Participant 11, end of case study 2

> I think it was good to do it—you know, it gave good results, you have the test data now to compare, you know that it's a good FEA model. I haven't really seen further use of the FEA model yet. It doesn't mean that I won't—I think that if it comes to that, it would be a great tool because you know that it's a good model to start with—but I haven't seen that happen yet. So I would say that, um, the option is out there right now in order to be able to do that, but I just haven't seen it used yet. … I could see the potential for it in the future.
>
> Participant 12, end of case study 2

Participant 12 elaborated on this potential for using the FEA model to guide future design changes.

> I think the FEA analyses that were ran can show where things can be improved if needed. I think that if you needed to make design changes, um, you know where to start, and how… You know where you can make changes with knowing where strengths and weaknesses are already in the design.
>
> Participant 12, end of case study 2

Overall, it appears the participants were expecting to see more tangible, direct evidence of FEA feeding into design decisions on this project. This suggests that seeing more product design impacts may have helped to illustrate the value of FEA to the participants and to validate its use in their minds. For example, FEA was used in the design of the battery housing to select an appropriate wall thickness (visible in the cross-section in Figure 49) that would ensure a sufficiently high first natural frequency while minimizing weight. This use of FEA was not presented to the participants as part of the intervention effort, but with the benefit of hindsight, it probably should have been. Seeing FEA used to guide early design decisions, followed by prototype testing and the collection of experimental data that validated the accuracy of the FEA and the design decisions it guided, may well have shaped the participants' views of FEA. Indeed, two of these same participants made interesting comments suggesting that the extent to which FEA should be used to guide design decisions is still an open topic in their minds.

> I'm not sure [the FEA] actually drove any true, major design decisions. So, um, I don't know if that's a good thing or a bad thing.
>
> Participant 11, end of case study 2

> If there was more time, I think some of the smaller design decisions might actually be integrated into this

> FEA, if we had someone maybe full-time on it or something like that. … And that may or may not be beneficial.
>
> Participant 7, end of case study 2

7.3.4 Long Reported Run Times Amplify Concerns About Time Required

The amount of time required to use FEA was an anticipated theme, on the part of both the research investigator and the participants.

> I think a big [factor] might just be time—just time that we have to spend on [the FEA], depending on how many other things are going on, because I know our schedule is packed, basically. That might actually be the biggest kind of factor in limiting its effectiveness.
>
> Participant 7, beginning of case study 2

> I may be wrong, but it was my perception that coming up with the models is a little time-consuming, and so I think the design could move faster than the modeling could. So I could see that being a limitation.
>
> Participant 11, beginning of case study 2

Even so, its prevalence as a theme in the data was notable. Of the terms included in the word frequency chart shown in Figure 69, 'time' was the fourth most common overall (after the much less surprising terms 'design,' 'FEA,' and 'testing') and the second most common in the normalized word count. During the interviews at the end of the project, all participants generally agreed that the FEA work was able to keep up with the product development effort. But additional comments by the participants illustrated a variety of perspectives, ranging from a focus on the more negative (e.g., using FEA takes a lot of time) to the more positive (e.g., FEA has the potential to save time overall).

> From a project management perspective, I see how much initial time and effort that needs to be put into developing the models and everything. That's not a trivial amount of time, it's certainly not a trivial amount of time depending upon the type of analysis run that you're doing on the computers and all that. … The amount of time it simply takes to, in some cases, develop the model and run the simulations… I think that's a pretty minor limiting factor.
>
> Participant 1, end of case study 2

> Time was definitely an issue for this project. [The research investigator has] been busy, but I think he was able to spend some time on the FEA models. But yeah, definitely time is a problem.
>
> Participant 4, end of case study 2

> I haven't seen anything to make me think that it's not feasible or that it won't work at this point. … I don't know what [the research investigator's] total time added up to building this model is, but it didn't seem like it was all he was doing for that period of time. It seemed like he was getting other work done as well. Especially if we can use it in the future, to answer design questions—I think that will actually save time rather than hurt us. It all depends on the project.
>
> Participant 7, end of case study 2

> I think that having the FEA model was really useful, to be able to kind of nail down where areas of concern might be, so you can focus your engineering effort in those areas… I think that's crucial to getting a good design out in a reasonable amount of time.
>
> Participant 13, end of case study 2

The presentations to the design team included information on the amount of time required to run the FEA models, which—as described in Section 7.2.3—had been somewhat longer than expected, especially for the shock analyses. These long run times were specifically noted by a few participants.

> I think, again, it's that run time. So you know, if these could run in 40 minutes, you know, instead of 40 hours, that's something which we would do much, much more often. But, it does take some time, so it's done less.
>
> Participant 7, end of case study 2

> I don't know how long it took him to develop the model, so I can't speak to that. I do know that running one version of his model seemed to be fairly reasonable, and was not a big deal, but one aspect was insanely long—one test he ran was something like 600 hours. So, that is completely unreasonable to have it be able to be impactful. I guess it all depends on how it's been modeled and what tests you're running—what simulation you're trying to run.
>
> Participant 11, end of case study 2

> Another thing is just the time it takes to actually run the models. That's just a fact of life… I think a lot of people kind of, you know—there is quite a bit of a time in investment in doing it, and if you're not able to do it quickly, then I think people kind of turn away from the idea altogether.
>
> Participant 13, end of case study 2

In retrospect, the research investigator may have done a poor job of coupling the open, honest communication about the total run times with an illustration of how the models could be used to address design questions. For example, running all permutations of the models (three vibration profiles and three shock profiles in three loading directions each) is an important exploration of the FEA model accuracy over the complete requirements space, but not the way the models would likely be used to support a design decision. Instead, a small subset might be selected based on the particular design change or concern (e.g., a specific direction and type of loading), and only that specific permutation of the model would be run, which would cut the 'run times' down by about an order of magnitude. Failure to clarify this for the participants may have taken a genuine issue—the amount of time required to use FEA—and made it seem worse than it actually was on this project.

7.3.5 Integrating FEA and the FEA Analyst Into the Design Process

Several participants used the term 'integration' during their interview responses, confirming it as a strong theme while also assigning it a surprising depth of meaning. One facet of this was *integration of FEA into the design process in a temporal sense*. For example, at the beginning of this project, Participant 12 noted how FEA usually lags the design effort.

> Most of the design is complete based on quick analysis/calculation, and many times the FEA is done afterwards to see the overall result.
>
> Participant 12, beginning of case study 2

At the end of the project, Participant 12 contrasted that typical experience with what was seen on this project. The consensus of the following comments was that for maximum impact, FEA needs to be done at least in parallel with design activities (Participant 12), if not sooner (Participant 11).

> I think on this [project], I really saw them go parallel, versus what I normally see, which is that the analysis is done after the design. I think on this one it was really work in parallel, and I think part of that was just because it was the same designer who was doing the analysis. … ***It's got to be done in parallel*** because a lot of times we can't wait for the design to be done and then create an FEA model, because it takes time away from the schedule. So ***it has to be completely integrated in order to make a real impact.***
>
> Participant 12, end of case study 2 (emphasis added)

> It seemed to me that maybe the modeling was done in parallel with the design. So, I think to be really effective, you might do the model first, and then help you drive design decisions. But I don't think that was the case here—I think it was mostly in parallel. So, ***if we want it to be more impactful, it might have to be done sooner***.
>
> Participant 11, end of case study 2 (emphasis added)

When participants were asked about the possibility of a full-time FEA analyst (with no mention in the interview question of the word 'integration'), they spoke of the importance of *an integrated role for the person performing the FEA*.

> I think the biggest factor for me would be ***how well they integrate into the design team and our testing team***. Either if it's one person… or if we have someone full-time modeling, ***I would like them to be intimately involved in kind of how our team structure is set up***. And so, the main part would be to break down communication barriers that could exist between FEA modeling, design, and testing of the design and models, which there are no barriers now, because [the research investigator] does all three. But if we did separate these functions, making sure that they are one team and they can all get the right information at the right time would be my biggest concern.
>
> Participant 8, end of case study 2 (emphasis added)

> I think early on, ***it's going to be very important that the FEA analyst and the design engineer work very closely together***, so that as changes are made in the design, the FEA person can also make those changes. ***It has to be very well-coordinated***.
>
> Participant 12, end of case study 2 (emphasis added)

> I think it really depends on the engineer who is doing the work. … ***It can work relatively seamlessly with the design, as long as you have someone who's well-integrated in the project*** and knows what's going on and can kind of keep up with the latest design decisions. So, you know, it depends on the engineer, but I think… it's definitely a feasible option and a useful tool.
>
> Participant 13, end of case study 2 (emphasis added)

The following comments (as well as most of the preceding comments) specifically identify the motivation for integrating the FEA analyst into the design team: ensuring that person's *familiarity with the design*, so that the FEA models are built in a manner that reflects *accurate knowledge of the product*.

> ***A full-time [FEA] person… would have to know the project.*** I think that's very important. Some sort of validation, sort of like what we did here, where we have testing to compare to these FEA results… That person—whoever does [the FEA]—has to be integrated in the team, basically, ***or at least know the product well. I think that's the biggest factor in confidence in the results.***
>
> Participant 7, end of case study 2 (emphasis added)

> ***If [the research investigator] did the design, he knows the intricacies of trying to create the FEA model at the same time.*** A lot of times what I see is one person does the design, and it's kind of farmed out for someone else to do the FEA, and that's where things can get lost because of, like, material properties, or how things get assembled together. So by doing both the design and the FEA, I think it really helped.
>
> Participant 12, end of case study 2 (emphasis added)

> The FEA designer would need to have a very good understanding of the product itself and the nuances behind it, and some of the details that go into the actual design of the product. I think that ***if they don't understand it very well, then they can't provide meaningful analysis as to what may be sensitive, or what components may fail or not***, based on, just different details. So that would be one thing, is to have a very good working understanding and a close relationship with whoever the mechanical designer would be.
>
> Participant 13, end of case study 2 (emphasis added)

Only one participant cautioned against a downside to having the same individual do both the design and the FEA.

> I guess what I didn't like about it is kind of a singular point of design, ***there wasn't really any diversity of thought.*** So, what if [the research investigator] didn't think through everything? You know, was he testing for everything appropriately?
>
> Participant 8, end of case study 2 (emphasis added)

7.3.6 Identifying a Model Implementation of FEA

Over the course of the case study, participants demonstrated a tendency to identify a 'model' implementation of FEA, and then frame and express their expectations for subsequent FEA applications relative to that model. For several participants, the model implementations they referred to were the FEA performed as part of this research. The strongest example of this was Participant 7. A major theme in this individual's comments was that an FEA model should be developed early, validated through testing, and then used to guide subsequent design changes and decisions. This view of how best to use FEA in the product development process appear to have been heavily influenced by the FEA work in Case Study 1 (Chapter 6). At the beginning of this project (Case Study 2), when asked how the use of FEA was most likely to be beneficial, Participant 7 responded with the following:

> … ***in sort of the same way in which we're starting to use it now.*** I think it's important to get an FEA model set up, and kind of set up early, and then kind of go through this initial round of testing, and see if you can validate any of those models in testing. And then, based on that, we could use it for, you know, a variety of things.
>
> Participant 7, beginning of case study 2 (emphasis added)

At the end of the project, on two separate occasions in the interview, Participant 7 reflected back on these expectations and offered an unsolicited comparison of the FEA from Case Study 2 to that from Case Study 1.

> ***Going back to Project 1, I know we actually used some of the original model that [the research investigator] built for Project 1,*** and we changed some loads on it, basically, and we saw that the response was very similar, and used that as an argument for not having to re-test the design with the slightly different weight. So that's exactly what I would have wanted to see, and that's good—that… aided us in our engineering judgment… that such a change was indeed kind of on the trivial side, and wouldn't affect our component much. … ***On Project 2, I haven't seen it much yet.*** It's like, the base is there, and I think, again, in the future, it could be used for that, but it just hasn't been yet.
>
> Participant 7, end of case study 2 (emphasis added)

> [On future projects] ***I think I would continue to want to see it used how it's used right now. I think it's working.*** … It doesn't seem like it bogs down anyone too much at the moment. We don't have a full-time person working on it that's kind of separated from the group. So I think I like where this is currently going. I'd still like to see the results—you know, if there's changes, can we use this. ***If we kind of use it how we used it on the first project, I think it could be very useful.***
>
> Participant 7, end of case study 2 (emphasis added)

This tendency was also evident in remarks made by other participants. When asked if there was any way they would definitely want to see FEA used, or NOT used, on future projects, they made unsolicited references to way FEA was used as part of the present work, though with a notable lack of conviction compared to Participant 7.

> I mean, without too much insight into other options—I think [the research investigator] did a good job of incorporating it into the design process, so I would probably push for that.
>
> Participant 4, end of case study 2

> If it's applicable, I would like to see FEA used in a very similar method, where we use it to help make early engineering decisions.
>
> Participant 8, end of case study 2

> I think if we had the time and money [in the future], I would suggest using it. I don't know that I would use it any differently than [the research investigator] has presented using it. It seemed like trying to show us the areas of concern for the mechanical model is what he was doing, and making sure it would pass testing. So I would try to do it the same way he did it.
>
> Participant 11, end of case study 2

A final example of this behavior was demonstrated by Participant 1. At the beginning of the project, this individual described an encounter with FEA many years earlier that was the model, in their mind, both of how to use FEA and of the types of benefits FEA can bring to product development.

> I was involved with [FEA]… on a project many years ago… where I saw how good, I think, FEA could be, and how much of a benefit it could be to a program. And I'm hoping on our program here that we'll be able to do that same type of thing as [the research investigator] develops and improves the models for our [circuit] boards and our system.
>
> Participant 1, beginning of case study 2

At the end of the project, Participant 1 was reminded of several instances when they had suggested specific uses of FEA over the course of the present case study (discussed more in Section 7.3.7), and then asked what makes FEA come to mind when they are thinking about a design problem. In their response, Participant 1 immediately returned to this earlier encounter with FEA and described the impact that it has had on their design thinking.

> I think it goes back to a project I was on quite a number of years ago, where I saw just how much FEA can assist in the design and test effort, and where it actually allowed

> us to—from looking at the model, expanding the model out, and using engineering judgment—to really being able to answer some questions that we probably could not test to. And yet we still had the confidence that, as long as we didn't push the model too much to the extremes, it was giving us good answers. So, from that… I've learned, over the years, that with the proper use of modeling, you can really expand your capabilities and improve the design.
>
> Participant 1, end of case study 2

7.3.7 Conceiving of New Applications for FEA

Participants frequently suggested using FEA to address various design questions or concerns that arose over the course of the project. In some instances, these were even design concerns that *they themselves identified*. The following summaries for selected participants highlight the most compelling evidence that using FEA to address vibration, shock, and other design issues was increasingly becoming a core element of the participants' design thinking.

Participant 1. On three separate occasions, this participant proposed using FEA to evaluate the structural response of an overall assembly in order to form early estimates (i.e., prior to physical prototype testing) of the vibration and shock amplitudes that various components in the assembly would experience. The participant first suggested this use of FEA regarding the two small electronics modules in the design (shown in Figure 45 and also visible in Figure 48 and Figure 49). This was a very insightful suggestion, and led to the research investigator doing precisely that: using the FEA model and results described in Sections 7.2.2 and 7.2.3 to provide early vibration and shock specifications to the electronics module product development team. The other two instances where this use of FEA was suggested by Participant 1 did not directly pertain to this design (Section 0) but involved related product development efforts. Participant 1 also proposed the idea of using thermal FEA modeling to perform an early characterization of self-heating effects, which was a known concern with the design.[22]

Participant 4. On at least two occasions, this participant proposed using FEA to guide design decisions related to the circuit board stack. One issue pertained to the placement or removal of several large electrical components located on the bottom (largest) circuit board. When the research investigator suggested that their presence (or absence) may couple into the structural

[22] Thermal FEA modeling was later used for this very purpose, but was completed by a different team and was not included as part of the present case study. The work is described in Scott et al. (2013) and Scott et al. (2014, in review).

response of the entire stack, this participant suggested using the FEA model to assess the issue. On another occasion, right after the research investigator presented the comparison of the prototype test data and the FEA results, this participant suggested using FEA to investigate design changes that might help reduce resonances of the circuit board stack. One idea they suggested was an asymmetric staggering of the circuit board mounting points (visible most clearly in Figure 53), to help break up mode shapes in which the entire stack participates simultaneously, such as that shown in Figure 55(a). Another idea was to convert the individual brackets that support the circuit board stack into one-piece 'rings,' in order to support the entire perimeter of the circuit boards. Overall, it was clear with Participant 4 that seeing the FEA and test results was fueling their thinking about how to improve the design.

Participant 7. At the end of the project, this participant suggested extending the use of these vibration and shock FEA models beyond the product design phase, to also address questions and design changes that typically arise during full-scale production and field support. This is an interesting example of 're-invention': using the same innovation (FEA) for the same demonstrated purpose (vibration and shock assessment) but in a different phase of the overall product lifecycle.

Participant 8. Over the course of the study, this participant asked three rather perceptive questions about FEA.

1. Can enough confidence be gained in FEA techniques such that FEA can be used in lieu of physical prototype testing on future projects?
2. Can FEA help address questions that arise due to late-changing product requirements?
3. Can FEA be used to verify and validate *requirements*? (i.e., to address the question, 'Are the product requirements correct?', rather than the question, 'Does the proposed design meet its product requirements?')

Separate from discussing the merits of these suggestions, it is interesting to note that each one strongly reflects this participant's self-described role in program management and systems engineering. In that sense, each suggested use represents an example of 're-invention': an alternate use (albeit suggested) of the same innovation to address the specific needs of that user.

7.3.8 Reservations About Using FEA on Future Projects

At the conclusion of the project, participants were asked whether, on future projects, they would be more likely to be skeptical of using FEA, or more likely to be an advocate of using FEA. Participants appeared to be fairly honest in their remarks: most said they would be advocates, while a couple refrained from using that word. But interestingly, nearly every one attached a caveat of some sort to their answer, giving insight into the reservations they still possess about using FEA in product development. Their comments themselves best illustrate the range of reservations they hold.

> ***I am definitely an advocate***, I think as long as you start out a project with the idea of using FEA so that you can put that into your schedule and ***understand that it takes time to get the initial models set up and working*** and it just gets folded right into the design process.
>
> Participant 1, end of case study 2 (emphasis added)

> ***I think I'd be an advocate, in a limited sense, at least***—that's what I got from this project. You can do something. With not a mountain of effort, you can get something that's reasonable. … Especially if we can use it in the future, to answer design questions—I think that will actually save time rather than hurt us. ***It all depends on the project.***
>
> Participant 7, end of case study 2 (emphasis added)

> ***I would definitely be an advocate***… but ***it would also depend on the makeup of the team and, you know—mostly if the design engineers believe that it would be beneficial.*** But I would definitely bring up my own experiences on this project on reasons why or how it could be beneficial.
>
> Participant 8, end of case study 2 (emphasis added)

> ***I wouldn't be more skeptical. I think I'd be maybe a hesitant advocate***, because I would like to use it, but ***it would all be based on time and money.*** … So I would like to use it, and I would like to see it be useful, I just don't know if our atmosphere is receptive to that. … We're always going to have to do the testing, whereas we're not required to have the model, therefore if money is limited, or time is limited, clearly one is going to win over the other. … While I'm not more skeptical, and I'm a little bit more of a believer, ***I just don't know if I could get it to be important in other people's minds who could control the money.***
>
> Participant 11, end of case study 2 (emphasis added)

> ***I still have mixed feelings about it.*** It really depends on the designer and the analyst. I think if the analyst and the designer know how to implement FEA correctly, then I would be a huge advocate for it… ***it really comes down to trusting the person who is doing it.***
>
> Participant 12, end of case study 2 (emphasis added)

When asked for ideas about how to take things that have been learned about FEA over the course of Case Studies 1 and 2 and leverage it forward to future projects, Participant 7 offered up a simple but insightful suggestion.

> It is nice that [the research investigator's] doing all of this, but ***hopefully he finds a way to kind of transfer his FEA knowledge***… It would be nice to see how he modeled it, why he modeled it, maybe some, you know, things that worked for him, things that didn't. I don't have a lot of knowledge on the details of those—the very intricate, you know, 'how did you mate this surface to this surface' and 'what's your boundary condition here.' It's like, 'oh, actually, for this type of screw I found that this boundary condition works well because it takes a lot less time but it gives similar results.' So ***getting those little details passed on to new engineers, especially if we're going to be the ones kind of doing it***—you don't have a kind of FEA expert doing it, and it's going to be in the engineers hands—***you have to teach the engineers to do it.*** And I'm picking up a little of it, but that's kind of just by forcefully asking him.
>
> Participant 7, end of case study 2 (emphasis added)

This is an interesting idea for a future diffusion effort: shifting the focus from *demonstrating* the use of FEA to teaching design engineers how to use it in the course of their work.

7.4 Discussion

This section presents a concluding discussion of the case study. Section 7.4.1 summarizes the case study findings and maps them back to the original research questions. Section 7.4.2 discusses several possible rival explanations for the case study findings. A more general discussion of the limitations of the research method was included in Section 5.8. The findings for this case study are further discussed in Chapters 8 and 9 in the context of the entire two-case research investigation.

7.4.1 Findings Mapped to Research Questions

This case study was conducted with the goal of answering the four guiding research questions identified in Section 1.4. The findings are summarized below in the framework of those questions.

RQ1. What are the product development team's perceptions of FEA? Participants in this case study demonstrated a notable tendency to identify a 'model' implementation of FEA, and then frame and express their expectations for subsequent FEA applications relative to that model. They generally attributed their confidence in FEA to one of two factors. The first factor was using experimental data obtained from physical prototype testing to validate the FEA results. The second factor to which confidence in FEA was commonly attributed was an overall confidence in the person performing the analysis.

***RQ2. How does FEA impact the team's design thinking*?** The data illustrate how various sources of design knowledge are leveraged in different combinations by each of the team members in order to establish design confidence in their own minds. Most participants indicated that FEA increased their confidence in the design, but several described other factors—such as experimental testing—that were prerequisite to FEA supplying any additional confidence. The impact of design similarity on the team's confidence was negligible, due to the newness of the design. The participants expected to see more tangible, direct evidence of FEA feeding into design decisions on this project.

RQ3. How do the team's views change on common barriers to adoption? Even though the participants generally agreed that FEA was able to keep up with the product development effort, their comments illustrated a variety of perspectives, with focuses ranging from more positive to more negative. In particular, a few participants focused strongly on the longer-than-expected run times for the FEA models. Participants also emphasized the importance of integrating the FEA analyst into the design team, in order to ensure that person's familiarity with the design and the incorporation of accurate product knowledge in the FEA models.

RQ4. How likely is the product development team to carry use of FEA forward? Most participants in the case study said they would be advocates for FEA on future projects, but nearly every one caveated their answer with some reservation they still possess about using FEA in product development. Several participants suggested FEA to answer specific questions that arose during the product development effort, offering compelling evidence that using FEA to address vibration, shock, and other design issues was increasingly becoming a core element of their design thinking.

7.4.2 Rival Explanations

In order to strengthen case study research findings, and in particular as part of an examination of internal validity, both Yin (2009) and Eisenhardt (1989) recommend the consideration of rival explanations.

One possibility concerning any of the more supportive things that were said about FEA by the participants in this study is that they were simply being supportive of the research investigator, who was a colleague and a full member of the product development team. The intent underlying the research design was to mitigate this potential bias in the data and findings by having other researchers conduct the interviews, giving participants the opportunity for honest reflection on their experiences.

The participants' views of FEA on this project could be clouded if they hold misconceptions about what questions this type of FEA is and *is not* intended to answer. For example, a common misconception involves the idea that this type of FEA directly answers the question of whether or not the parts in the design would 'break' during vibration and shock testing. But overall, this type of misconception does not appear to be pervasive in the participants' thinking. On the contrary, several participants offered reasonably accurate assessments when they summarized their view of what FEA provided for this product development effort.

> I think there are some pretty good advantages, one being that we can't instrument the entire system in every location, and so the FEA—if it agrees at the locations we did instrument—we can trust it at locations that we couldn't instrument. So we can get ideas for levels that we would see on different locations on the boards, or other locations that we just couldn't instrument.
>
> Participant 4, end of case study 2

> The main thing [FEA] doesn't do right now, is it still doesn't answer the question whether something will break or not. It kind of tells us the levels that we're going to see, and we don't have a way of saying, 'Is this okay? Is our sub-component going to survive this environment, given these levels?' So I think that's the main limitation we have, at least with the method that [the research investigator] is using. I think there might be other methods which are more time-intensive and require much bigger models that might be able to answer that. So that's kind of a limitation, and it's kind of a play with

> time and model size. … We can kind of use it for what [the research investigator] kind of intended to, which is comparisons—making sure that certain design changes don't increase levels, or modes—there's peaks in the frequency response that we don't like to see, and if there are, we could figure out how to mitigate those, or say that they're low enough that we could deal with them.
>
> Participant 7, end of case study 2

> It seemed like trying to show us the areas of concern for the mechanical model is what he was doing, and making sure it would pass testing.
>
> Participant 11, end of case study 2

> Having the FEA model was able to show where possible weak points were in our design. And so then we were able to kind of instrument and pay close attention to those areas when we did our actual testing. And so that gave us, I think, the most useful data out of our testing, which is beneficial for the design as a whole because you're able to test at the weakest points, and if those perform well, then you know that the system as a whole will perform well.
>
> Participant 13, end of case study 2

Finally, one participant made the frank observation that FEA had a biased opportunity to keep pace on this product development effort because of the external motivation posed *by this research investigation*.

> I think it kept up because [the research investigator] was really focused on doing it, and because he was doing it also as kind of his school work. If he just had to—if he hadn't had that as a purpose, it may have fallen to the wayside because of priorities—not necessarily because we didn't think it would be useful, but because if you felt crunched for time, and you're going to test anyway, you might say the model is not as important.
>
> Participant 11, end of case study 2

This is an honest and fair explanation that cannot be fully refuted. An implicit aim of the research effort was to demonstrate on a real product development effort whether (or not?) using designer-friendly commercial FEA software for vibration and shock modeling of electronics packaging designs is *possible*, which can be defined in terms of reasonably concrete metrics. Is the software capable enough? Are the results accurate (or even close to accurate 'enough')? Can the analysis be completed in time? These questions can be answered (via demonstration) using the present research design, despite the external motivation posed by the investigation to the product development effort. However, demonstrating that FEA is *feasible* immediately crosses into a murky middle ground. How much of the individual's time is required? How much of the team's overall resources (budget, schedule, personnel, etc.) are devoted to FEA? How much experience is required? How much effort or commitment is required? These metrics—though definable—inherently involve a judgment call as to what an appropriate or realistic 'balance' is. In that sense, the question of FEA's ultimate feasibility for any given product development effort cannot be 'answered' in an absolute sense by this or any research design or diffusion effort. Rather, the best that can be achieved is to demonstrate the potential presented by such an approach and let users and stakeholders make their own judgments.

7.4.3 Results of Member-Checking

A draft of this case study report was submitted to all participants for review, in order to solicit feedback on the appropriateness of the conclusions drawn by the research investigator. Each participant was provided a copy of the draft in which direct quotes from their interview transcripts were highlighted in yellow, as well as any other statements pertaining to them, to ensure that they reviewed and agreed with the usage and interpretation of the case study data by the research investigator. All seven case study participants responded to the request for feedback, each of whom expressed concurrence with the findings presented, either verbally or in writing.

A few participants took the opportunity to offer more reflection on this research. One participant expressed that they would have felt slightly more comfortable being interviewed by the research investigator, rather than by the interviewers from Stanford. They recalled feeling a need to say 'nice' things and to not be overly frank about the research investigator or about FEA, since they were speaking to an independent third party with whom they were not familiar. However, this participant also emphasized that their comments were honest and the interpretations offered in the case study report were accurate.

Another participant provided a very honest reflection on the overlap in the investigator's role as a researcher and FEA advocate.

> One thing I do want to mention, and I'm not sure if you realize this or not, but ***my experience with FEA has been very limited, and a lot of the experience I do have has been shaped by you***, since you are our resident expert on the subject. I don't know how that fits in to your

> general thesis/study, and if that makes me a biased responder or not. ***Am I just parroting what you want to hear?*** Or maybe you are surprised at some of my responses (which are probably a combination of my interpretations of things about FEA you've said, and how I've seen others react to the limited FEA I've seen at Sandia)?
>
> (Participant 7, after reviewing draft case study report)

Despite this concern and the researcher's role as an advocate for FEA (which was factored into the research design, as discussed in Section 5.8.2), this participant on numerous occasions emphasized points that were clearly their own view on what makes sense for FEA in product development, especially by the conclusion of the second case study. Examples include the following:

- honest statements regarding the apparent feasibility and accuracy of using FEA in the manner of the case studies;
- identification of the FEA implementation on the first case study as a 'proof-of-concept', and the importance of utilizing lessons-learned going forward, rather than simply using FEA just for the sake of it;
- specific statements about how FEA did not have all the same impacts in the second case study as in the first;
- emphasis on the importance of validating FEA models with test data, and an original suggestion to use FEA for investigating whether small design changes required a second round of prototype testing; and
- the need for passing on the research investigator's FEA techniques to newer engineers who are interested utilizing it.

While this participant's understanding of FEA (and other participants, as well) was informed by the case studies and the involvement of the investigator, the findings stand as valid answers to the guiding research questions.

8 Cross-Case Analysis

This chapter compares and contrasts the individual case studies described in Chapters 6 and 7. Yin (2009) and Eisenhardt (1989) emphasize this step as distinct from both the individual case analyses and the final synthesis of generalized findings (Chapter 9). Section 8.1 compares and contrasts the details of the case study projects themselves, such as the nature of the product development efforts, complexity of the products and the FEA, and the team composition. Section 8.2 compares the findings from the two case studies in the framework of the four guiding research questions outlined in Section 1.4. Finally, Section 8.3 compares the case study design projects and teams to Sandia overall, as well as instances where the case study findings were not in agreement with the Sandia Context Assessment findings (Chapter 3). Instances where there was strong similarity between the case study and Context Assessment findings are included in the final synthesis and discussion presented in Chapter 9.

8.1 Comparison of Cases

The two case studies used in this research shared a variety of common traits, but also differed in several important ways. The following sections compare and contrast the two cases. A summary of this comparison is included for reference in Table 27.

Table 27: Comparison of two case studies.

	Case Study 1	Case Study 2
Context	Sandia National Laboratories	Sandia National Laboratories
Teams	9 participants + 1 investigator Similar to Sandia overall in composition and previous FEA exposure	7 participants + 1 investigator Similar to Sandia overall in composition and previous FEA exposure
Design task	Modification of existing design 3 design concepts generated	New, aggressive design 1 design concept generated
Investigator role	FEA analyst; mechanical design engineer on predecessor design	Mechanical design engineer and FEA analyst
Intervention strategy	*(Same strategy used for Case Study 1 and Case Study 2)* FEA used to model design concept, results presented to team prior to prototype fabrication and testing FEA validation data collected during prototype testing FEA results compared to test data, comparison presented to team	
FEA details	Mechanica software 3 concepts analyzed 3-week model development time (calendar-time) 40-hour run time per concept for full suite of vibration & shock analyses FEA model subsequently refined to better match test data	Mechanica software 1 concept analyzed 1-month model development time (calendar-time) 1-week run time for full suite of vibration & shock analyses No subsequent FEA model refinement
Timelines	Conceptual design to prototype test spanned 8 months Approx. 8-month data collection on participants	Conceptual design to prototype test spanned 16 months Approx. 15-month data collection on participants

8.1.1 Teams

The product development teams for the two case studies shared many similarities. The team compositions were quite similar in terms of the members' technical backgrounds, self-described roles, and length of employment at Sandia, as summarized in Table 20 and Table 23. The teams were also very similar in terms of the fraction of participants who had previous exposure to FEA. The two teams were similar in size and shared several members, as depicted in the Venn diagram of Figure 70.

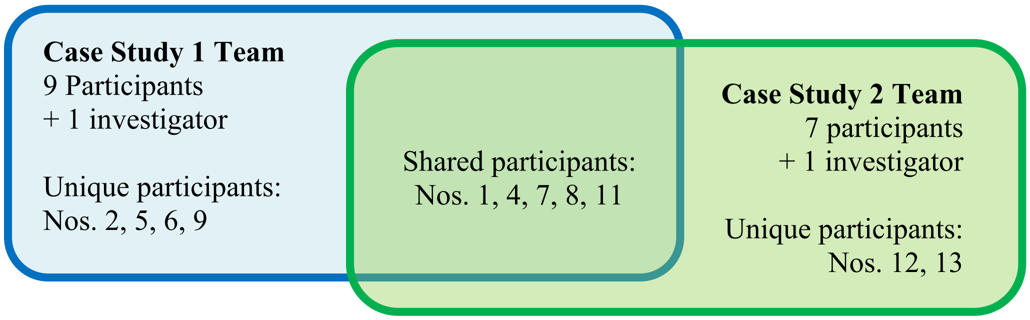


Figure 70: Overlap of participants for case studies 1 and 2.

One notable difference between the two cases was the role of the investigator. For the first case study, the investigator performed the FEA, while another team member was the mechanical design engineer. However, the investigator had been the mechanical design engineer on the existing version of the electronics assembly, and so was quite familiar with the design and the previous testing it had undergone. On the second case study, the investigator was the mechanical design engineer and also performed the FEA.

8.1.2 Products

Both case studies involved the development of electronics packaging designs that are intended to function in severe vibration and shock environments, and therefore require a high degree of ruggedness. Beyond this general similarity, the products being developed in the two case studies differed in an important way.

The first case study entailed modifying an existing packaging design to incorporate a separate electronics module that also was already in existence. Both the electronics assembly and the smaller electronics module had undergone a substantial amount of previous testing. Because of this, the product development team began the effort with a relatively high degree of confidence in each of these stand-alone designs in terms of their performance in vibration and shock environments. The design task essentially became one of incorporating the two existing designs into one new, combined designed that maintained as much of that existing design confidence as possible, in order to maximize the likelihood of successfully passing vibration and shock testing. Achieving this essentially entailed the following:

- minimizing changes to the electronics assembly in terms of its overall geometry and circuit board form factor; and
- mounting the smaller electronics module on the electronics assembly in a manner and/or location that prevented it from being exposed to higher vibration and shock levels than it had previously been tested to.

Three design concepts were evaluated, and in the end, the concept that was selected was the one the best satisfied these two overarching design goals.

The second case study involved the development of an altogether new design, so there was no goal of maintaining similarity to an existing product. In addition, the combination of required design elements (a large battery pack, two small electronics modules, and substantial circuit board area) with a restrictive volume allowance made the overall design task more aggressive than that of the first case study. Because of the new and unproven nature of the design, the product development team had a strong need to establish confidence that the design was sufficiently rugged to meet its vibration and shock requirements. Only one design concept was analyzed in detail, largely due to time constraints and the overall complexity of both the design task and the FEA model.

8.1.3 FEA Details

The FEA modeling that was performed in each case study product development effort was identical in several regards. In each case, FEA was used to perform a modal analysis of the product design, followed by both random vibration and mechanical shock analyses. All analyses were linear and were performed using Mechanica, a designer-friendly FEA package that is integrated with Pro/Engineer 3D modeling software.[23]

The experimental data collected during prototype testing was a type that is routinely collected during vibration and shock testing—namely, acceleration PSDs for random vibration and acceleration time-histories and shock response spectrums for mechanical shock. This eliminated the need for any special equipment during prototype testing, and minimized the additional burden imposed by collecting data for FEA model validation.

Moreover, both implementations of FEA were intentionally designed to enable a direct, side-by-side comparison of the FEA results with experimental data. This provided all interested

[23] Mechanica is now Creo Simulate, and Pro/Engineer Wildfire is now Creo Parametric. Both are made by Parametric Technology Corporation.

members of the product development team the opportunity to perform their own visual and quantitative comparison of the FEA results to the experimental test data, including those team members with no prior exposure to either FEA or vibration and shock testing.

Despite these similarities, some differences existed between the cases, the biggest of which was in terms the time required to build and run the FEA models. For the first case study, the FEA models took about 1-1/2 months at approximately 1/2 full-time-equivalency (i.e., the equivalent of about three calendar weeks) to develop, de-bug, run, and pull together the results for *all three* design concepts. Once the models were successfully setup and debugged, running the full suite of vibration and shock analyses required about 40 hours per design concept. On the other hand, for the second case study, the FEA models took about four months at approximately 1/4 full-time-equivalency (i.e., the equivalent of about one calendar month) to develop, de-bug, run, and pull together the results for *just the one* design concept. Once the models were successfully setup and debugged, running the full suite of vibration and shock analyses took over one week of calendar time—and even that amount of calendar time was compressed by running analyses in parallel using three Mechanica licenses. Detailed information on the FEA model run times for Case Studies 1 and 2 is compiled in Appendices K and L, respectively.

A second difference between the cases was the level of accuracy achieved with the initial version of the FEA models. In the first case study, the test data suggested some very specific areas of focus for improving the FEA model, so an effort was made by the research investigator to refine the FEA model. In the second case study, the initial FEA results were more accurate overall than in the first case study, and the test data were less suggestive of specific areas to focus on for improvement. So this final step of refining the FEA model based on the test data was not performed.

8.1.4 Intervention Strategy

For both case study projects, a structured intervention approach was used for implementing FEA in the product development process and for introducing the study participants to FEA. A more detailed description of the intervention strategy is included in Section 5.5. In this approach, FEA was deliberately performed after conceptual design, but prior to assembly and testing of a functional prototype. Next, a physical prototype was tested to demonstrate whether or not the electronics functioned appropriately during application of the vibration and shock loads—a routine step in the 'design-build-test' process. In addition, this prototype testing was used as an opportunity to acquire the data needed for validating the FEA models. The test data were then compared side-by-side to FEA model predictions, and the comparison was presented to each of the product development teams. The overall intent of this approach was to expose the study participants to the predictive capabilities (or limitations) of FEA in a very transparent fashion.

Beyond these common aspects, some details of the exact intervention steps differed between the two cases, as shown graphically in Figure 71. For example, in the first case study, three design concepts were analyzed, so the initial presentation included a comparison of all three concepts and an assessment of the preferred concept based on the FEA results. In the second case study, FEA was only used to assess one design concept, which is all that was presented to the rest of the product development team.

Another key difference was in regard to the final step of refining the FEA model based on the validation data, as discussed in Section 8.1.3. In the first case study, some effort was made to refine the FEA model, and the results were shared with the product development team along with a discussion of the modeling lessons learned. In the second case study, this final step of refining the FEA model was not performed, so no further presentations or reports were shared with the team.

Finally, some differences existed in the method of communication that was used at the various intervention steps—namely, whether a presentation was given in-person or a report was distributed by email. These differences are shown in the red ‘communication’ boxes of Figure 71.

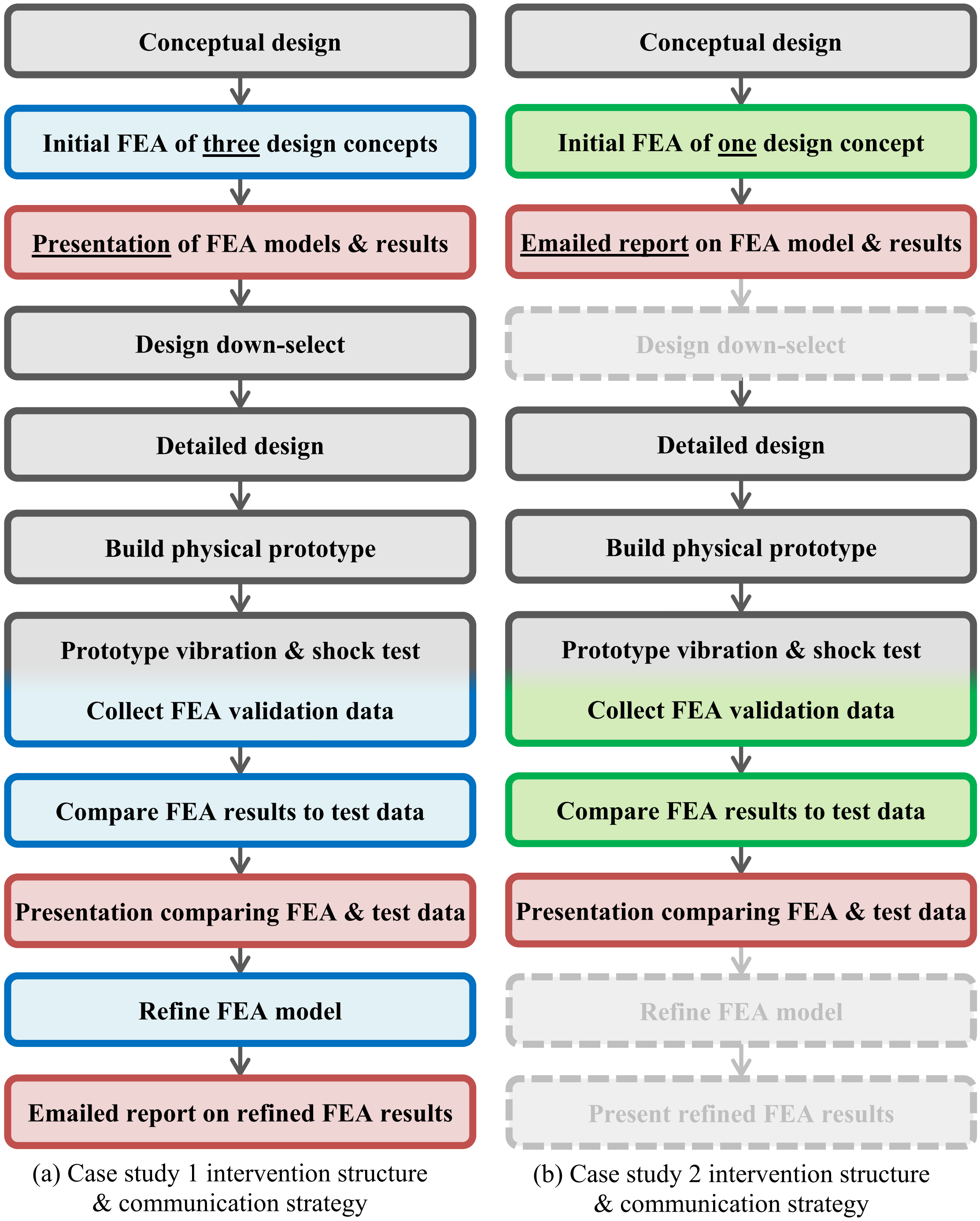


Figure 71: Comparison of intervention and communication for two-case study.
Routine steps in the 'design-build-test' product development process are shown in gray. Steps involved in implementing FEA for vibration and shock analysis are shown in blue and green for case study 1 and 2, respectively. Red boxes denote strategic points of communication about FEA to the product development team. Differences included the number of design concepts analyzed, the exact combination of in-person and emailed communication, and whether or not the FEA model was refined and re-presented to the team near the end of the project. (a) Case study 1. (b) Case study 2.

8.1.5 Timelines

While the two case studies followed the same overall product development approach and FEA intervention strategy, they differed in the span of the overall timelines.

Overall, the timeline for the first case study was fairly condensed, due to the combination of the customer deadline and the nature of the design project itself, which was essentially a modification of an existing design. As shown in Figure 15, approximately eight months were devoted to the typical product development steps, including conceptual design, down-selection, detailed design, prototype fabrication and assembly, and laboratory testing. Similarly, about nine months were required for the FEA intervention activities, including the initial model development, comparison of the FEA results to test data, and FEA model refinement. The total span of data collection on the participants in the first case study, from the FEA survey to the first FEA interview, was also about eight months.

The timeline for the second case study was roughly double that of the first. This was again due to both the customer deadline and the nature of the project itself, which entailed the development of a new, relatively aggressive design. As shown in Figure 46, approximately 16 months were devoted to the typical product development steps, including conceptual design, detailed design, prototype fabrication and assembly, and laboratory testing. About 11 months were required for the FEA intervention activities, beginning with the initial model development and concluding with the comparison of the FEA results to the test data. The total span of data collection on the participants in the second case study, from the first FEA interview to the second FEA interview, was about 15 months.

8.2 Comparison of Findings

This section compares and contrasts the findings from the two cases in the framework of the four guiding research questions. The intent is to look for replication across cases, which strengthens and increases the generalizability of the findings (Yin, 2009, p. 54; Eisenhardt, 1989). Differences in the findings are also highlighted and discussed in the context of the differences between the case study projects themselves.

8.2.1 Perceptions of FEA (RQ1)

The first guiding research question was, *What are the product development teams' perceptions of FEA?* In this area, the findings from the two case studies were remarkably similar.

One emergent theme in this research and a finding from both cases was the fact that the participants typically did not have much confidence in FEA a priori. Rather, their comments about FEA—both in terms of past experiences with it, and their experiences on these case study projects—revealed that *their confidence in FEA had to be earned*, or established. In each case, two factors were by far the most commonly-cited by participants as the source of their confidence in FEA. The first was seeing a *direct comparison of the FEA results to experimental data* obtained from testing of a physical prototype. It was clear that the teams perceived FEA by means of its ability to accurately predict, or match, the results of physical testing. The second common source of confidence in FEA was an overall confidence *in the person* performing the FEA. This second factor was clearly supported by the results of the research investigation, but must be caveated with the fact that for both cases, the research investigator was the person performing the FEA.

Another finding replicated in both case studies was the strong influence of previous encounters with FEA in terms of shaping the participants' perceptions and expectations of FEA in these product development efforts. The participants referenced previous encounters with FEA that were in some instances positive in nature, and in other instances negative. For example, some participants had a very positive encounter with FEA on a past project, and consistently described it in a way that revealed it was the 'model' in their minds, both in terms of how to use FEA, and in terms of the benefits that FEA can provide. For one individual who was a participant in both case studies, their 'model' was the use of FEA on a previous project that they referred on numerous occasions throughout the entire investigation. For another participant in both cases, their 'model' became the use of FEA on the first case study, and they specifically noted that FEA was not used to the same extent on the second case study. Other participants made very specific references to negative experiences with FEA on past projects, and it was clear how those experiences directly tied over to their strongest views on how FEA should (or should not) be used in product development efforts.

8.2.2 Impact on Design Thinking (RQ2)

The second guiding research question was, *How does designerly FEA impact the teams' design thinking?* In this area, the findings from the two cases are consistent with each other, but lack the direct similarity that was evident in the findings for the first research question. Instead, these findings support each other in a complementary manner, and reflect the somewhat fluid reasoning that designers use when solving design problems.

The first finding was that the product development teams, on the whole, described FEA as a means to obtain *design confidence*. The first aspect of their design confidence pertained to the selection of one particular design concept to carry forward to prototype testing. This was present in the first case study only, since it was the only case that involved the analysis of multiple concepts. The second aspect of their design confidence pertained to whether or not the [selected] design concept would perform adequately in testing. This was cited by participants in both case studies. Interestingly, these two elements of their design confidence represent a *relative* question (i.e., 'Has the *best* design concept been selected?') and an *absolute* question (i.e., 'Is the design *good enough*?').

However, another finding from both case studies was that participants never described FEA as a stand-alone source of design confidence. Rather, they seemed to leverage different combinations of design knowledge from various sources—physical testing, design similarity, and/or FEA, depending on the situation—to establish their own confidence in the design, with *FEA tending to serve a supporting role*. A comparison of these results at different stages in each case study is shown in Table 28. Most notably, the one instance in all of this research where FEA had perhaps the greatest opportunity to serve more than a supporting role and to contribute substantially to the design confidence of the teams was in the second case study, prior to prototype testing. The reason is that in that case study, no other significant sources of design knowledge about the proposed design concept existed prior to prototype testing, because it was an altogether new design. However, rather than elaborating on how FEA increased their confidence that the design would perform well in testing, the comments from most participants in the second case study reflected a state of suspended judgment, forward-looking to the point in time when the prototype testing was completed. A certain amount of design knowledge and confidence *that could only come from prototype testing or design similarity* seemed to be prerequisite in their minds before FEA could supplement that confidence. This result could also be interpreted in light of the earlier finding that they simply lacked confidence *in the FEA* until such time as it had been validated with experimental data.

Part of this outcome might also be explained by the circumstances of the second case study project. Much of the research investigator's intent behind the design of the intervention was to expose participants to the accuracy with which FEA could [potentially] predict the results of experimental tests, even for new, complicated designs. This goal was achieved, but at the expense of spending more time exposing the product development teams to the use of FEA for other tasks, such as making decisions during conceptual design, or seeking out opportunities to use FEA to support smaller design decisions *after* the model had been validated with prototype testing. This was essentially the remaining finding on the second case study project: the participants expected to see more tangible, direct evidence of FEA feeding into design decisions.

Table 28: Comparing sources of design confidence in the participants' thinking.

	Design question	**Factors emphasized by participants**	
		Case Study 1	**Case Study 2**
Design process progression (i.e., time) ↓	Was the best design concept selected?	Design similarity was most important. FEA helped, but to a lesser extent.	N/A (Only one concept analyzed.)
	Confident the design would pass vibration/ shock testing?	Design similarity was most important. FEA helped, but to a lesser extent.	Design similarity was not present as a factor. FEA helped, but the team was primarily awaiting the results of prototype testing.
	After testing, confident the final design is sufficiently rugged?	Results of prototype testing were most important. FEA helped with subsequent, small design decisions.	Results of prototype testing were most important. FEA *could* help with subsequent, small design decisions, but the need was not encountered.

8.2.3 Views on Common Barriers to Adoption (RQ3)

The third guiding research question was, *How do the teams' views change on common barriers to adoption?* The 'barriers' focused on early in this research included the time and cost associated with FEA, as well as the issues of accuracy, communication, and assumptions.

The time required to utilize FEA was a surprisingly tenacious barrier in the minds of the participants, a finding that was replicated in the two case studies. It was essentially a known issue going in to this research, and was confirmed as a widespread point of concern in the pilot research. But in the first case study, this concern persisted for the participants even after exposure to what most viewed as a relatively successful use of FEA in the product development process. In the second case study, while the consensus among the participants was that FEA was able to keep up with the product development effort, their comments illustrated a variety of perspectives, with focuses ranging from more positive to more negative. In particular, a few participants focused strongly on the longer-than-expected run times for the FEA models that were encountered. Collectively, for these two cases, there appeared to exist some hesitancy on the part of the product development teams to translate positive experiences into general beliefs that FEA can be utilized within the time constraints of a typical product development effort.

In the first case study, the importance of effective communication about FEA emerged as a strong theme, with participants citing a variety of enabling factors, such as co-location of the FEA analyst with the rest of the design team and an open style of communication about FEA. In the second case study, participants emphasized the importance of an integrated role on the product development team for the person performing the FEA, in order to ensure that person's familiarity with the design and the incorporation of accurate product knowledge in the FEA models. Taken together, these findings might best be interpreted as *primarily* underscoring the importance of achieving a *high level of integration of design and FEA activities* in the product development process. This can be achieved or aided in more than one way, such as co-location of the FEA analyst with the rest of the design team, or having the design engineer and the FEA analyst be the same individual. The *aim* of this integration is to overcome an underlying communication problem that becomes operative when the FEA analyst's role is not well-integrated into the larger team.

Finally, the product development teams in both case studies expressed an overall satisfaction with the level of accuracy achieved in the FEA results, especially in the second case study. But beyond that approval, the impact of the FEA accuracy on the design teams' views appeared to be marginal. If anything, the finding replicated in these case studies is that reasonable accuracy of FEA results is only *the first step* in securing a foothold in the design team's thinking and achieving a real impact in product development.

8.2.4 Likelihood of Carrying FEA Forward (RQ4)

The final guiding research question was, *How likely are the product development teams to carry use of FEA forward?* In this area, the results from the two case studies were similar, with one major finding replicated between the two.

On the one hand, some indicators in the two case studies gave mixed results. By the conclusion of the first case study, several participants appeared to have an increased openness to using FEA on future projects as a result of that experience—but not *all* participants. At the conclusion of the second case study, when asked directly, most participants said they would be advocates for FEA on future projects, but nearly every one caveated their answer with some reservation they still possessed about using FEA in product development.

On the other hand, in both case studies, there were multiple occasions where participants conceived of their *own* applications for FEA to answer questions that arose during product development. In many instances, these proposed applications of FEA were to answer design or testing questions related to vibration and shock—i.e., the same type of FEA that was used by the research investigator, but in response to issues or concerns that the *participants* themselves identified. Such occurrences offer compelling evidence that the product development team members were adopting FEA into their design thinking. In yet other instances, in addition to being initiated by participants, the proposed applications of FEA were related to—but not exactly the same as—the way FEA was applied by the research investigator. For example, the suggested applications included designing experimental test setups, analyzing self-heating effects, and developing and verifying product and sub-component requirements. This 're-invention' was replicated in both case studies and—based on decades of diffusion research (Rogers, 2003)—is a predictor that FEA will continue to be a factor in the participants' design thinking in the future.

8.3 Comparison To Sandia Overall

This section presents a discussion comparing these two case studies to the broader product development environment at Sandia. Section 8.3.1 compares the product development projects and the use of FEA to a wider range of Sandia's development work. Section 8.3.2 compares the product development teams to the overall Sandia community, based on the Context Assessment Results (Chapter 3). Section 8.3.3 contrasts the case study and CAS findings, highlighting areas where they were different and offering possible explanations. Instances where there was strong similarity between the case study and CAS findings are not further discussed here, but are included in the final synthesis and discussion presented in Chapter 9.

8.3.1 Product Development Projects

This section compares the case study product development projects and use of FEA to a wider range of Sandia's development work.

Type of FEA. The use of FEA for modal, vibration, and shock analysis finds wide applicability at Sandia, where many classes of products are designed for rugged environments. Using FEA for designerly investigations of dynamic response presents a big opportunity for conceptual design, because design engineers typically lack a strong background and intuition in structural dynamics. However, Sandia also utilizes FEA for stress analysis, thermal analysis, and electromagnetic (EM) field simulation, in addition to altogether different simulation technologies such as computational fluid dynamics (CFD), electrical and electronics simulation, and multi-physics simulation. The case study findings may find applicability in these areas.

FEA software. The FEA for the case study projects was performed using Mechanica, the integrated FEA software available with Pro/Engineer solid modeling software[24]. Mechanica is used occasionally, but not frequently, by full-time FEA analysts at Sandia. Its capabilities are much more limited than Sandia in-house FEA codes and other commercial FEA software. The case studies were designed with this in mind and were intended to stand in contrast to the majority of projects at Sandia.

Class of products. In particular, the design of rugged electronics represents a significant portion of Sandia's product development work, so the case studies findings should find applicability across much of Sandia in this regard. In addition, Sandia's development work includes a mixture of new product design as well as modifications of existing products, so the two case studies are nicely representative of this diversity.

Project timelines. The case study projects focused on a class of products that involve short design-build-test development cycles relative to other classes of products at Sandia. As a result, the case studies may be strongly applicable to other Sandia products with similar development timelines, and less applicable to projects with longer timelines. These case studies may hold more or less applicability outside Sandia, depending on the industry and its product development timelines.

[24] Mechanica is now Creo Simulate, and Pro/Engineer Wildfire is now Creo Parametric. Both are made by Parametric Technology Corporation.

8.3.2 Product Development Teams

The individual case study teams were introduced near the beginning of each case study report, in Sections 6.1.2 and 7.1.2, respectively. As shown in these sections, both case study teams were representative of Sandia Context Assessment pre- and post-data in terms of their technical backgrounds, length of time at Sandia, present roles at Sandia, and overall familiarity with FEA. This similarity supports the external validity of the case study findings across the wider Sandia product development community over the time period of the two-year investigation.

One notable contrast with typical projects was that the FEA for the case studies was performed by the research investigator, who was an integral member of the product development teams. This included being co-located with the majority of the other team members, as well as sharing the same line management with them. The case studies were designed with this in mind and were intended to stand in contrast to the majority of projects at Sandia.

8.3.3 Findings Contrasted With Sandia Context Assessment

This section contrasts the case study and CAS findings, highlighting areas where they were different and offering possible explanations. Instances where there was strong similarity between the case study and CAS findings are not further discussed here, but are included in the final synthesis and discussion presented in Chapter 9.

Dollar cost of FEA not a factor in case studies. The CAS revealed a strong tension within the product development community's views regarding the dollar cost of using FEA (Section 3.3.2). A large majority of respondents who received the question indicated they had seen the cost of FEA be a factor in the past, but comments were evenly split between the ideas that FEA can reduce cost and that FEA costs too much. In the case studies, most participants did not offer any strong views on this issue. This is likely due to the fact that only a few members of the case study product development teams dealt with budget issues on a regular basis, so issues surrounding dollar cost were simply not visible to them. For those team members who did address budget issues, their feedback was essentially that cost was not an issue, since the person performing the FEA (the investigator) was already on the team and budgeted for, and was able to perform the FEA without an impact on other responsibilities and deliverables to the team. This does not mean the FEA for these case studies was free. It simply means the dollar cost of utilizing FEA did not stand out as a particularly visible or contentious issue to the case study participants.

Several modes of using FEA not addressed in case studies. Respondents to the CAS described various other modes in which FEA can be used, such as for design optimization, identifying and analyzing weak points in a design, and diagnosing failures that occur in prototype testing (Sections 3.3.1 and 3.3.7). The case studies were not focused on using FEA for design optimization or for identifying and analyzing 'weak points' in the design (at least, not in the sense of performing stress analysis). The potential existed to use FEA for diagnosing test failures, but none occurred in the case studies. As such, other modes for using FEA were not strong themes in the participants' interview responses.

Other commonly-cited problems with FEA not encountered in case studies. Respondents to the CAS described a variety of negative views and past experiences with FEA. These included instances in which improper use of FEA or poor FEA modeling assumptions lead product development teams astray with inaccurate information (Section 3.3.1). This type of negative experience did not show up in the participants' interview responses. Another issue in the CAS results revolved around the complexity of real design problems and of using FEA effectively. The idea that real design problems are too complex for FEA was a strong theme in the CAS-pre data. In contrast, the CAS-post included the idea that FEA models are often unnecessarily complicated, as well as the theme that FEA results are too uncertain and are not trustworthy or accurate (Section 3.3.6). Participants in both case studies definitely commented on some of the inaccuracies in the FEA model predictions, especially in the first case study, but their comments did not indicate that they were given an overall poor impression of the accuracy that can be obtained with FEA, or that the complexity of the models in the case studies were a poor match for the complexity of the design problems being addressed.

9 Synthesis and Discussion

> All professional roles are embedded in an institutional context, but not all practitioners take it seriously. A mechanical engineer may see himself as a technical problem solver, treating his relations with his clients as an unavoidable but essentially nonprofessional activity. Or… he may frame his tasks in such a way that a larger social context moves to the foreground and technical problem solving becomes a piece of the larger social puzzle. If institutional context occupies a central place in a practitioner's role frame, then he pays attention to the phenomena for which there is no satisfactory off-the-shelf theory. He must construct a theory of his own. And if he treats his theory of the context as an object of reflection… then he will perceive that others in the situation meet his frames and theories with frames and theories of their own. He will see them not only as objects to be planned for but as planners in their own right, and his interaction with them will take the form of a reflective conversation.
>
> Schön (1983, p. 274-275)

Corbin and Strauss (1990) describe an analysis process that becomes more abstract at each stage, moving from identifying concepts in the data, to grouping related concepts into categories, and finally building these categories into constructs. This chapter represents the final phase in that process. Section 9.1 discusses the importance of providing positive examples of FEA in product development. Section 9.2 presents the concepts of outcome and efficacy expectations from the field of cognitive psychology, and further compares key findings to extant literature. Section 9.3 presents the Confidence Model, a framework intended to illustrate how using FEA to build confidence in a product design is related to the process by which product development teams gain or lose confidence in FEA itself. The model describes how using FEA in a way that meets a team's outcome and efficacy expectations increases their motivation to rely on it in their product development approach, and, conversely, how failing to meet those expectations has the opposite effect, reducing their openness to FEA. Section 9.4 offers recommendations to Sandia National Laboratories, rooted in the findings from this research, to promote an enhanced yet balanced utilization of FEA in product development. Section 9.5 summarizes the contribution of this research to the fields of FEA, design, and design research, and the limitations and applicability of this research are assessed in Section 9.6. Finally, Section 9.7 concludes the chapter with suggestions for future research.

9.1 Providing Exemplars of FEA in Product Development

Several of the concepts addressed throughout this research relate to the fundamental question of *how* best to use FEA in the product design and development process. In general at Sandia National Laboratories, product designs may be evaluated utilizing analytical and/or experimental means. The decision of which type of evaluation to use (or whether to use both) is typically left to the discretion of the product development team, with input from customers and stakeholders. This flexibility of approach is intended to empower product development teams to utilize resources (time, money, personnel) in a manner consistent with the needs and scope of their projects. The case studies in this research were used to investigate designerly FEA (described in Chapter 4), which was introduced into the routine design-build-test product development process. The intent was to work within the resource constraints of real projects and to leverage existing testing, while deliberately exposing the product development teams to FEA's potential and limitations (outlined in Section 5.5). The case studies focused on vibration and shock analysis of electronics packaging designs, but this method of implementing FEA while demonstrating its use to a larger team can almost certainly find application for other classes of products and other applications of FEA in product development.

Interestingly, the research findings underscored the importance of providing such exemplars [25] of FEA in product development. The views and expectations held by several participants in the case studies were strongly influenced by previous encounters with FEA, a phenomenon which Adams and Askenazi earlier noted.

[25] Here, 'exemplar' is used to describe "an admired person or thing that is considered an example that deserves to be copied" (Merriam-Webster.com, 2015).

> Those who are not intimate with the finite element method will certainly harbor some misconceptions about the ease of use or the degree of accuracy entailed. It is interesting to note that nonusers or casual users with similar levels of exposure can have diametrically opposed viewpoints on these issues. *Typically, most preconceptions are based on some defining experience with the technology.* … However they came about, misconceptions about the capabilities and limitations of the technology at any level of the organization can slow or stunt the growth of simulation in the design process.
>
> Adams and Askenazi (1999, p. 21, emphasis added)

Providing a positive example of FEA proactively harnesses the tendency observed in this investigation to fixate on *one defining encounter* with FEA, equipping product development teams with a practical understanding and realistic expectations of how the technology can be used. Exemplars of FEA also serve to counter the various negative perceptions and past encounters with FEA that were demonstrated to exist in the product development community through the Sandia Contest Assessment (Chapter 3).

Once they are provided with positive examples, product development teams will engage in design thinking and naturally explore their own particular uses. This behavior was replicated in both case studies and exemplified by several participants, who on multiple occasions conceived of their *own* applications for FEA to answer questions that arose during product development. Such re-invention has been observed in a variety of diffusion studies and is a predictor that FEA will continue to be a factor in the participants' design thinking in the future (Rogers, 2003, p. 183-184, 429). But one example from recent literature was that reported by Donaldson, who investigated the transfer of innovative practices introduced at large African welding firms to the 'informal sector' of side jobs and weekend work in which many welders participated (2004). It was expected that any transfers of innovative practices would be recognizably similar to those introduced, but instead, Donaldson observed the African welders adapting the introduced techniques to better suit their particular needs.

In any effort to provide exemplars of FEA to the product development community, an important goal should be to ensure that the benefits gained from using FEA are worth the investment of the team's resources, *as judged by the team*. It is their perceptions of FEA that affect its rate of adoption, not the perceptions of management or FEA experts and advocates (Rogers, 2003, p. 223). Other important factors identified in this research are discussed below, and corresponding recommendations to Sandia are presented in Section 9.4.

Importance of true integration with the design process. This investigation—and the second case study, in particular—revealed the high level of importance placed by the product development teams on achieving a strong integration of FEA into the design process. This included integration in the temporal sense of the design process, an integrated role for person performing FEA, and the analyst's overall familiarity with the design, which is important for ensuring the FEA reflects accurate product knowledge. These themes echoed those from the Sandia Context Assessment, in some instances precisely mirroring the negative themes from the CAS, such as the need for improved alignment of FEA activities with project needs; the need to clarify scope and expectations for FEA; and the negative effect that performing FEA in isolation has on the influence of FEA in product development (Section 3.3.4). The case studies suggested that better integration is one means to achieve improved communication between design teams and the person(s) performing FEA about the assumptions and limitations inherent in FEA models, a separate topic that also garnered substantial attention in the CAS.

Similar findings were recently reported by Bailey et al., who studied the offshoring of FEA model building activities by a major American automobile manufacturer (2012). The investigators recounted the historical use of mathematical models by automotive companies preceding this shift. Originally, lumped parameter vehicle models were used to analyze vehicle performance but played no role in design, so the task dependence between engineering groups and the mathematical model builders was very low. By the early 2000s, FEA models had replaced the early lumped parameter models, and looked so similar to the actual cars that they resembled digital animations of physical crash tests. This inadvertently lead engineering managers to believe that mathematical models could ultimately replace physical analysis. As the role of FEA in design grew, it was moved into the standard product development process. As such, the task dependence of design engineers and FEA analysts grew, but the FEA analysts—who were still located at the U.S. headquarters—had access to the physical crash test items, which they often spent hours poring over and inspecting when simulation results did not match test results. Later, when FEA model building was moved overseas to reduce costs, problems were encountered because the analysts no longer had access to the physical hardware, or to the design engineers on whom they depended for crucial information and understanding of the design. The investigators concluded their study with the following admonition.

> Ultimately, the creators of simulations must return to the objects or people that they aim to represent to test and validate their models. Each subsequent change in the model requires yet more validation. Thus, with simulation, physical objects or other people become deceptively distant but remain absolutely vital… Simulations with high verisimilitude appear to substitute for objects or other people because one can do within representations what one could previously do only with physical entities themselves. *The adequacy of such simulations, however, still depends on validating their results against physical objects, people, and their associated processes.* … Managers... should structure simulation work such that people have ready access to the physical entities and processes they model.
>
> Bailey et al. (2012, emphasis added)

FEA one of many sources of design knowledge. Achieving integration with design involves being able to use FEA in a manner that is befitting of the way designers *think*. In many applications, FEA is not required to be a stand-alone source of design knowledge, but is instead one source in an overall process that consists of synthesizing information from many sources. This is the nature of designing, and skilled practitioners of design are accustomed to this manner of thinking (Cross, 2007; Schön, 1983). The case studies revealed participants leveraging various combinations of design knowledge to establish design confidence in their own minds. Interestingly, the Sandia Context Assessment suggested a possible growing use of FEA to shape engineering judgment (Section 3.3.5). Taken together, these findings suggest that exemplars of FEA in product development should reflect this adaptability, allowing engineers to *design their approach to building design confidence* as warranted by the particular situation.

9.2 Outcome and Efficacy Expectations

A useful construct from the field of cognitive psychology for viewing several findings from this research was provided by Bandura in 1977. In this seminal work, Bandura presented a model of behavioral change in which he introduced the idea of *self-efficacy*, distinguishing between outcome expectations and efficacy expectations as shown graphically in Figure 72. He defined outcome expectations as “a person’s estimate that a given behavior will lead to certain outcomes,” and contrasted this with efficacy expectations, which are “the conviction that one can successfully execute the behavior required to produce the outcomes.” The difference between the two is important, because “individuals can believe that a particular course of action will produce certain outcomes, but if they entertain serious doubts about *whether they can perform the necessary activities* such information does not influence their behavior” (Bandura, 1977, emphasis added).

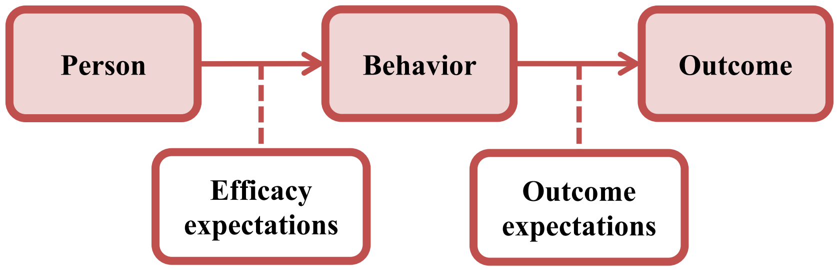


Figure 72: Efficacy expectations and outcome expectations, from Bandura (1977).
An outcome expectation is a person's belief that a given behavior will lead to certain outcomes. An efficacy expectation is the person's conviction that they can successfully perform the behavior required to produce the outcome.

The influence of efficacy expectations is not limited to the *choice* of behavior, but also determines how much effort people expend, and how long they persist, in the face of obstacles (Bandura, 1977). Additionally, a feedback is present: successful execution of "subjectively threatening" activities further reinforces a sense of efficacy, whereas 'giving up' in the face of aversive experiences allows "self-debilitating expectations" to persist (Bandura, 1977).

To be clear, Bandura's research focused on the concept of self-efficacy to explain changes achieved in fearful and avoidant behavior in *individuals* (1977). In contrast, the goal of this investigation was to draw conclusions regarding the impact of designerly FEA on product development *teams*. Nevertheless, if using FEA in product development is treated as the 'behavior' in question—along with the associated investment of time and effort required to do so—this adaptation of his original model offers an insightful framework. The adapted model is shown in Figure 73. Whereas Section 9.1 discussed the fundamental question of *how* best to use FEA in product development, this construct is particularly useful for describing other findings that pertain to the fundamental questions of *why* to use FEA, and whether or not it is *feasible* to use FEA within the practical constraints of a typical project.

This model echoes recent findings reported by Leonardi (2009), who investigated the link between a failed implementation of new simulation software at a major American automobile manufacturer and the users' interpretations of that simulation technology. Leonardi proposed that technology implementations fail when a misalignment exists between users' *social* and *material* interactions. He defined social interactions as discussions people have with colleagues about a new technology, which essentially result in the formation of expectations about what a new technology is, what it is intended to do, and how it might therefore help them in their work. He defined material interactions as actual encounters with the technology that are obtained through directly using it for themselves. In Leonardi's model, a new technology is not likely to be adopted when material interactions do not live up to interpretations of the technology that have been formed based on social interactions—a closely related idea to that presented here of the teams' *expectations*. Interestingly, in the particular case study that Leonardi investigated, the initial interpretations that users' had formed were factually incorrect and represented a misconception of what the new technology was designed to do. The software was intended to do much more than the engineers realized, and it in fact could have helped them improve how they work in ways that they were very much in favor of changing. But because they misunderstood what the software was for, and it did not live up to the expectations they had formed, they rejected it, despite a push by management to use it and despite their own expressed support for changing how they worked. Based on these findings, Leonardi emphasized the importance of understanding "… not just… what technological artifacts can or cannot do, but… how and why people come to believe that they do or do not do those things" (2009).

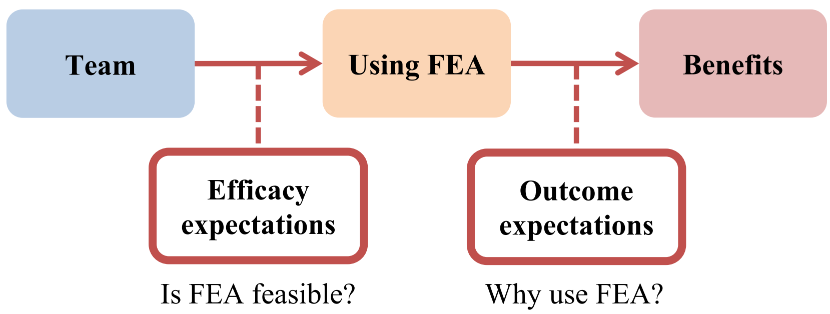


Figure 73: Adaptation of Bandura's model to product development teams using FEA.
Bandura's model applied to individuals, but here is applied to teams, with 'using FEA in product development' as the behavioral change under consideration. Answering the question 'why use FEA?' for product development teams can be viewed as a matter of addressing their outcome expectations. Answering the question 'is it feasible to use FEA?' for the product development team can be viewed as a matter of addressing their efficacy expectations.

9.2.1 Addressing Outcome Expectations

For a product development team, the value added by FEA is measured in terms of material contributions to their overall task, which itself consists of two main elements:

- *designing a product* that meets an identified set of needs; and
- *developing confidence* that the product in fact meets those needs and all derived performance specifications—a strong theme in the case study findings.

Answering the question '*why* use FEA?' for the product development team can be viewed as a matter of addressing their outcome expectations. The team will be more motivated to rely on

FEA as part of their product development approach if they expect that its use will be effective and provide beneficial outcomes. In contrast, the team will be much less motivated to incorporate FEA into their approach if they do not actually believe its use will provide some tangible benefit to their overall product development task.

Figure 74 depicts this construct in relation to the product development process, including feedbacks from influential outcomes of using FEA that were identified in this research. The feedbacks are included because the benefits provided to the product development effort (or lack thereof) serve to either reinforce or diminish the team's initial set of outcome expectations. For example, if FEA is used as part of a product development effort, but the team does not discern any meaningful contribution that FEA provides to their overall goal, their collective outcome expectations will be negatively impacted. If the team does recognize some meaningful assistance provided by FEA, their expectations will be positively impacted. The most influential outcomes identified in this research are further discussed below, and corresponding recommendations to Sandia are presented in Section 9.4.

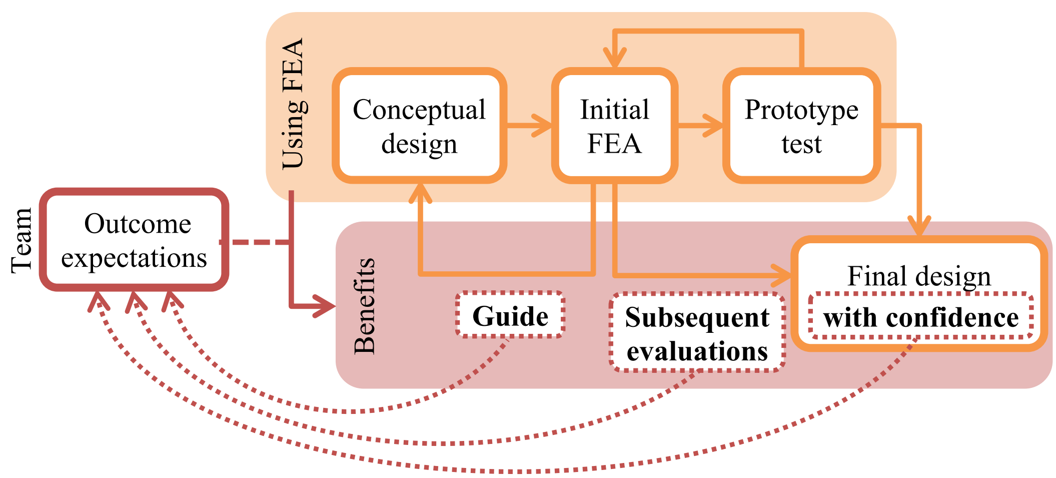


Figure 74: Outcome expectations attached to the use of FEA in product development.
A team will be more motivated to rely on FEA as part of their product development approach if they expect that its use will be effective and result in beneficial outcomes. Influential factors identified in this research include beliefs that using FEA will (1) directly impact the product design or guide decisions, (2) facilitate evaluation of small design changes that occur after prototype testing, and (3) enhance the overall sense of confidence in the design. Feedbacks from these factors are shown, since observed outcomes either reinforce or diminish the team's initial expectations.

Product development teams value product design impacts. A theme throughout the data collected in this research was the importance to the team of using FEA in a way that *tangibly impacts product design*. Designing a complex product involves a long chain of decisions, so it is perhaps natural for a product development team to expect FEA to contribute materially in this regard. Guiding design decisions and optimizing designs were frequently-cited examples in the Sandia Context Assessment (Section 3.3.1). The case study results were consistent with this. Participants in the first case focused on the use of FEA to down-select from multiple design concepts. Conversely, in the second case study, participants specifically noted the absence of any direct product design impacts.

Purpose of using FEA is to improve design confidence. In the Sandia Context Assessment Survey, the most commonly-cited advantages of using FEA were for improving and optimizing designs, guiding design decisions, and identifying and analyzing the weak points in a design (Section 3.3.1). In the case studies, participants emphasized in a more general sense that the goal of using FEA in product development is to *improve design confidence*. In addition to directly impacting the product design (discussed above), other ways to employ FEA include (1) using a validated FEA model to analyze the impact of small design changes that occur *after* prototype testing (as in case study 1); or (2) using FEA to build confidence in decisions that are primarily driven by other factors, such as a strong sense of engineering judgment rooted in some other source of design knowledge (as in case study 1) or inflexible design constraints (as in case study 2). Compared to driving decisions, these may represent somewhat more ethereal contributions from FEA. But there was evidence from the case studies suggesting that when certain other factors are present, such as a prototype test regimen or strong design similarity to previously-tested products, this is the dominant way that the team employs FEA in their design thinking.

9.2.2 Addressing Efficacy Expectations

A product development team is tasked with designing a product and establishing confidence that it meets user requirements, but must do so while adhering to budget allocations, meeting schedule end-dates, and utilizing available personnel—who collectively possess a wide, though finite, variety of skills and expertise. A team can believe that using FEA will result in certain positive outcomes, but that belief alone will not influence their behavior if they possess serious doubts that they are capable of using FEA within their project's constraints. Answering the question 'is it *feasible* to use FEA?' for the product development team can be viewed as a matter of addressing their efficacy expectations. The team will be much more motivated to rely on FEA as part of their product development approach if they believe they possess the necessary resources to use it successfully, and much less motivated to utilize FEA if they do not possess this belief.

Figure 75 depicts this construct in relation to the product development process, including feedbacks from influential factors identified in this research. These factors are integral aspects of using FEA in product development and serve to either reinforce or diminish the team's initial set of efficacy expectations. For example, if a team commits to using FEA on a project, believing they possess the resources to do so, but the FEA is not completed in time to assist the team's effort in any meaningful way, their collective efficacy expectations will be negatively impacted. If the use of FEA keeps pace with project needs and decision points, their expectations will be positively impacted. The most influential factors identified in this research are further discussed below, and corresponding recommendations to Sandia are presented in Section 9.4.

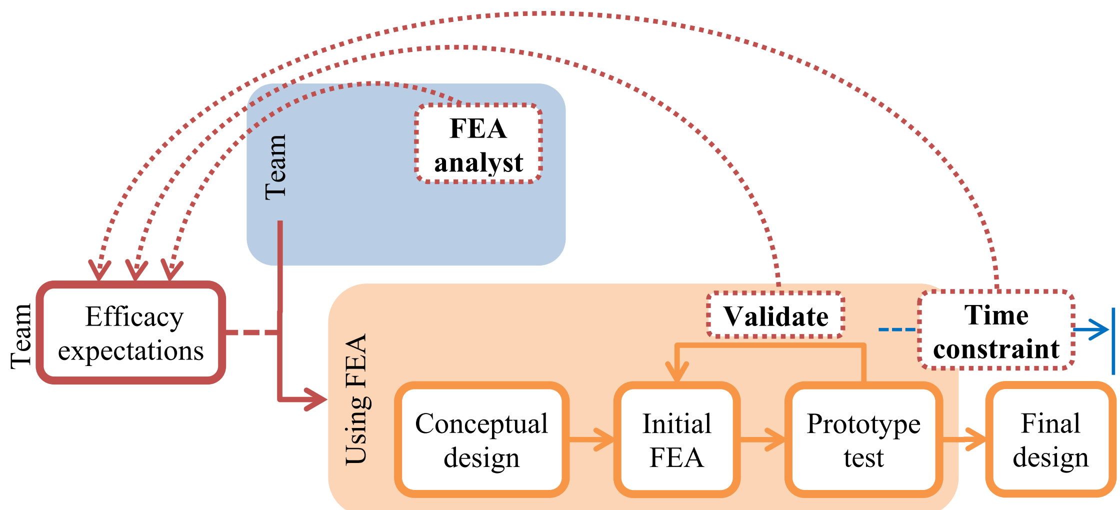


Figure 75: Efficacy expectations attached to the use of FEA in product development.
A team will be more motivated to rely on FEA as part of their product development approach if they believe they possess the necessary resources to use it successfully. Influential factors identified in this research include (1) confidence in the accuracy of FEA, achieved by direct comparison with test data, (2) confidence in the person performing the FEA, and (3) belief that FEA can be used within the time constraints of the project. Feedbacks from these factors are shown, since encounters with FEA either reinforce or diminish the initial expectations.

Direct comparison of FEA and test data earns confidence. For FEA to be beneficial, it must be sufficiently accurate to correctly guide the thinking and decision-making of the product development team. The requisite level of accuracy is driven by the specific manner in which FEA is utilized—e.g., whether for relative or absolute questions, for very specific predictions or for general 'ballpark' guidance, etc.—and varies accordingly. In any case, the finding from this research is that demonstrating accuracy with a direct comparison of FEA model predictions and experimental test data to increase the design team's confidence in FEA is not only extremely effective but also *necessary*. Such an approach directly confronts existing perceptions, when they exist, that FEA results are too uncertain, not accurate, or not trustworthy. In their investigation of FEA practices at a major American automobile manufacturer, Bailey et al. reported a similar finding, noting that “Despite management's pressure to treat the simulations as adequate evidence, design engineers often distrusted the models *until they saw the same results in physical tests*” (2012, emphasis added). However, both of the present case studies also demonstrated that the accuracy of FEA results is only one element of a product development team’s outcome expectations that must be addressed.

Confidence in the analyst is necessary for confidence in FEA. Confidence in FEA must be earned, and one of the two primary ways it is achieved is having an established confidence in the FEA analyst. This topic was present in the Sandia CAS-pre data (Section 3.3.6), but its significance was not recognized by the research investigator until the case studies were conducted, where it became a major theme. Participants frequently identified confidence in the person performing the FEA as an essential factor in establishing their overall confidence in the use of FEA. At the team level, this amounts to a belief by the team about its own capacity to successfully utilize FEA in product development, even if it is only one individual or a small subset of the team members that actually performs the FEA.

Difficult to overcome perception that FEA takes too long. This research quickly identified the importance of the issue of time required to use FEA, which received more comments in the Sandia CAS-pre than any other issue. The comments reflected a clear tension between the potential that FEA holds to identify design issues early in development, and the perception that FEA takes too long to impact design. The case studies underscored the influence of beliefs about the time required to utilize FEA, which was a surprisingly tenacious barrier in both cases. Even after exposure to designerly FEA that kept pace with the overall product development timeline, the teams still appeared hesitant to translate those positive experiences into general beliefs that FEA can be utilized within the time constraints of a typical project.

9.3 Confidence Model

The Confidence Model, shown in Figure 76, represents a final synthesis of the findings from this investigation. The model is so named because of the central role that confidence plays in the variety of activities and dependencies involved. In essence, it embodies a description of how using FEA to build confidence *in a product design* is related to the process by which the product development team gains or loses confidence *in FEA itself*.

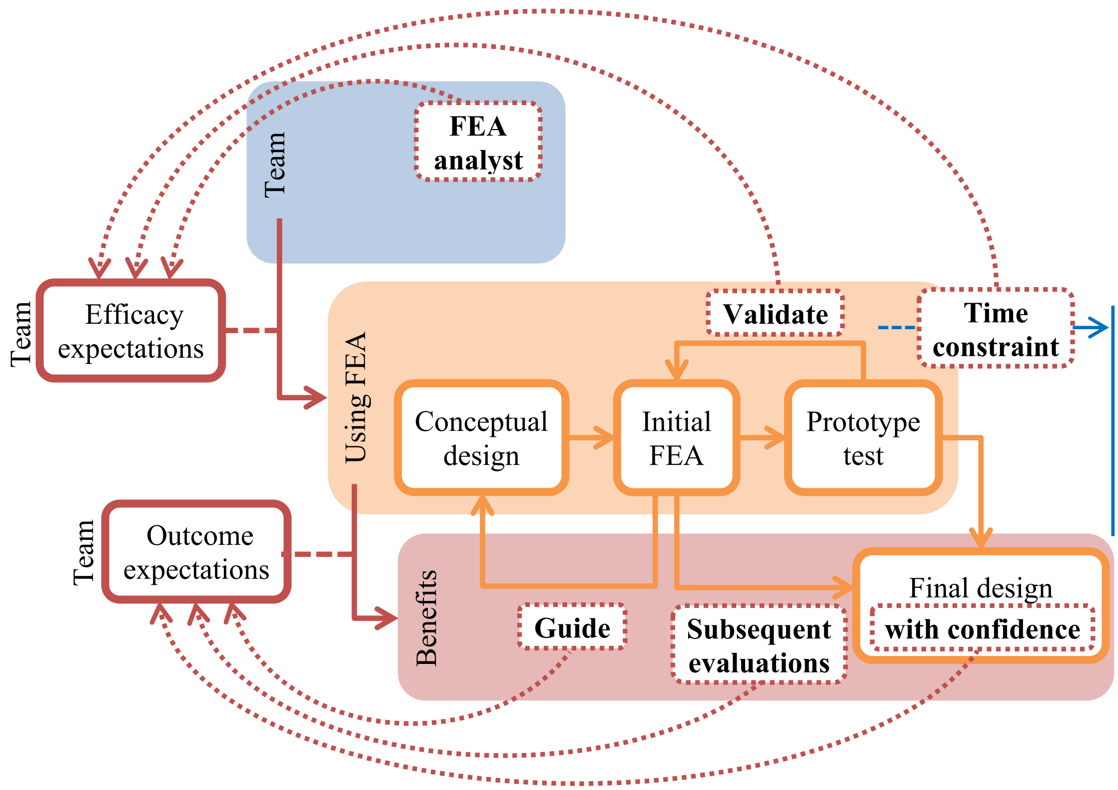


Figure 76: Confidence Model, annotated with factors identified in this research.
When FEA is observed guiding design decisions and contributing to design confidence, it promotes positive outcome expectations. When FEA is scoped to fit within project schedules and accurately predicts design performance as validated by experimental test data, it promotes positive efficacy expectations. Enhancing these expectations increases a team's motivation to rely on FEA in their product development process. Negative experiences with FEA involving these key factors tend to diminish expectations, thereby decreasing a team's motivation to rely on FEA.

When a team observes FEA guiding design decisions and contributing to an overall improvement in design confidence, it promotes positive outcome expectations. In other words, it provides the team with favorable answers to the question, '*why* should we use FEA?' Enhancing outcome expectations increases the motivation of the team to rely on FEA in future product development efforts. In contrast, when outcome expectations are diminished due to negative experiences with FEA, a team's motivation to rely on FEA suffers. This occurs, for example, when the team does not discern any meaningful contribution from FEA to design decisions or design confidence.

Similarly, when a team observes FEA being expertly applied and scoped to fit within project schedules, and accurately predicting design performance as validated by experimental test data, it promotes positive efficacy expectations. In other words, it provides the team with favorable answers to the question, '*can we* use FEA to predict design performance, given our resource constraints?' Enhancing efficacy expectations increases the motivation of the team to rely on FEA in future product development efforts. In contrast, when efficacy expectations are diminished due to negative experiences with FEA, a team's motivation to rely on FEA suffers. This occurs, for example, when FEA results are not accurate enough to be useful, or when using FEA takes too long relative to a project schedule, or when the person performing the FEA is not perceived as competent by the other members of the product development team.

The connections between the design process and outcome and efficacy expectations are significant, because *several elements of the activity itself*—that is, of using FEA in product design and development—*are irreplaceable and unavoidable determinants of outcome and efficacy expectations.* The factors identified in this research are inextricably coupled to the act of designing a product and developing a defendable level of confidence in it, while working within a team's time and resource constraints. Most, if not all, of the identified factors would be difficult to reproduce simultaneously and convincingly in a contrived demonstration. Similarly, there is no avoiding the negative impact on outcome or efficacy expectations in the product development community when teams encounter a genuine attempt to use FEA and these key expectations are not satisfied. The paradigm represented in this focus on expectations aligns strongly with the findings of Leonardi (2009), who emphasized the link between addressing the expectations of technology users and, ultimately, the ability to successfully implement new technologies and achieve organizational change.

> Managers and implementers may be wise to attend to the social interaction environment into which a new technology is implemented. ... [They] may wish to introduce information into users' contexts of social interaction that aligns with the experiences those users will have when they engage in material interactions. ... *If the information users glean from their material interactions negatively qualifies the information they generate in their social interactions, they will stop using the technology and may unwittingly resist even those organizational changes of which they are in favor*.
>
> Leonardi (2009, emphasis added)

9.4 Recommendations to Sandia National Laboratories

The following recommendations, rooted in the findings from this research, are offered to Sandia National Laboratories for promoting an enhanced yet balanced utilization of FEA in product development. These findings and recommendations should find applicability across a broad portion of Sandia's development work, as the teams in the two case studies (Chapters 6 and 7) were strongly representative Sandia product development community, based on the Context Assessment Survey (Chapter 3).

Target product development activities where FEA can enhance design confidence. This research revealed that above all else, product development teams view the purpose of FEA as improving confidence that their designs meet performance requirements. Conversely, they view FEA negatively when, for one reason or another, it fails to serve this purpose. Future diffusion or intervention efforts should specifically target applications where FEA is well-suited to unambiguously enhance confidence in product performance. This requires an informed view of both FEA technology itself and the potential product development applications where it might be most beneficial. Though FEA is impressive, advocates should take great care to avoid any hint of the view that it is somehow a good fit for all types of products and needs.

Demonstrate the applicability of FEA for evolutionary and/or experimentally-tested products. FEA is often only one of many potential sources of design knowledge. In such instances, FEA can only rightfully be used if it provides value in the presence of these other factors, which may hold a strong precedence in the minds of the responsible product design engineers. Future diffusion or intervention efforts should consciously demonstrate ways in which FEA can contribute to enhanced design confidence, even when prototype testing is required or strong similarity exists to previously-tested designs. Doing so may be very effective at introducing FEA to an untapped audience of design engineers, who will conceive of their own applications for intelligently leveraging FEA alongside experimental product testing and/or for relative questions aimed at making existing products better.

Emphasize tangible impacts to product design. This research revealed that of the various manners in which FEA can enhance design confidence, product development teams hold a particularly strong expectation that FEA should directly impact product design. As a result, they take note when the use of FEA does not result in demonstrable changes in the physical configuration of the product. Exemplars of FEA in product development should be selected that exhibit significant feedback from FEA into the product design itself, rather than only verifying that the product design was adequate, or only demonstrating that FEA can accurately predict experimental data (although each of these also important elements of a diffusion effort).

Involve FEA analysts in testing, and ensure the visibility of FEA validation activities. This research revealed that confidence in FEA must be earned, and that an effective and necessary step in achieving this is providing direct comparisons of FEA results and experimental test data, so that teams can judge the merits and adequacy of FEA for themselves. This seems like a fairly obvious point, but its effectiveness and importance cannot really be overstated. Team meetings are probably the most effective venue for this type of information sharing, but project reports, internal white papers, and/or seminars might reach an even wider audience. Consideration should be given to presenting validation metrics that, when possible, are familiar and intuitive to the product development team. This should ensure that the effectiveness of the FEA modeling capability is not misunderstood to be either better or worse than it actually is. To facilitate this, FEA analysts should be more directly involved with prototype testing during product development. However, this research suggested that demonstrating the accuracy of FEA results is only the first step toward securing a foothold in a design team's thinking, so this recommendation should not be given undue priority over the others listed here.

Explore co-location of FEA analysts and design teams, or FEA training for design engineers. This research revealed that confidence in FEA must be earned, and that an essential step in achieving this involves securing the product development team's confidence in the person performing the FEA. This demands stronger ties between the community of FEA analysts and experts and the product development community. To this end, Sandia should explore embedding FEA analysts more fully in design teams, and/or co-locating FEA analysts with project and design groups to enhance comradery. Another option would be to explore FEA classes and training for interested design and project engineers. In any case, Sandia should be diligent to prevent placing newer or less-experienced FEA analysts in project assignments without a reasonably clear path forward on how FEA can assist in the team's product development task. For example, very difficult or ambiguous projects should require the participation, or at least oversight, of an experienced FEA analyst who is familiar with product development needs and challenges.

Strive for strong alignment between FEA and product deliverables. This research revealed the importance placed by the product development community on achieving a true integration of FEA into the design and development process. It is the opinion of the research investigator that achieving an improved level of integration is largely dependent upon experts in FEA understanding the product development process and knowing how to use FEA in such a way that maximizes its benefits while minimizing the additional burden it places on the development team and its resources. To that end, Sandia should consider deliberate actions to ensure that the goals and deliverables for both project teams and their FEA experts are consistent. This consistency should span several aspects of Sandia's product development work, including project budgets and schedules, research and advanced development, research publications, interfacing with customers and stakeholders, requirements formation, conceptual design and design optimization, prototype assembly, test planning and execution, quality control, safety, security, project documentation, and manufacturing.

Expertly scope FEA to fit project timelines using a designerly approach. This research revealed that it is difficult to broadly overcome the perception, where it exists, that using FEA takes too long to be practical for real product development. Future diffusion or intervention efforts concerned with securing the confidence of product development teams should make every possible effort to demonstrate that the use of FEA can be expertly and reliably scoped to fit within the constraints of project schedules. All possible trade-offs in terms of modeling techniques, scope, fidelity, accuracy, and/or uncertainty should be considered and weighed alongside project-specific needs, which may (or may not) be able to make use of less-capable models in return for quicker model development and run time. This type of trade is especially important for classes of products with a strong conceptual-design element, short development times, and/or established prototype testing practices, as they may present a particularly strong opportunity to utilize designerly FEA.

9.5 Contribution

Decades of extensive research surrounding FEA have focused on extending the capabilities of FEA codes to address evermore complex phenomena with increasing accuracy. The need for FEA to evaluate practical problems that arise in design practice—especially the aerospace and automotive industries—has spurred the development of commercial FEA codes, with huge strides made in recent years toward more designer-friendly FEA software. Yet despite the size of the market and the potential that is perpetually attributed to FEA for impacting design, relatively little research has occurred to develop a significantly deeper understanding of the variety of negative perceptions surrounding FEA that persist in the product development community, and to understand how they are interrelated.

This research was aimed at addressing that gap, with a particular goal of better understanding the factors that are operative in either promoting or inhibiting a deeper assimilation of FEA into product design and development. The investigation relied on case study applications of designerly FEA and participant-observer research methods to identify and explore important factors in the thinking of real design teams at Sandia National Laboratories, an established research and development institution.

The research findings provide insight into several fundamental factors that inhibit a more complete acceptance and utilization of FEA by product design and development teams. The Confidence Model offers an parsimonious framework for synthesizing the major results of the investigation, which is a goal of theory-building case study research (Eisenhardt, 1989). It describes how the activity of using FEA in in the design process uniquely and unavoidably shapes the outcome and efficacy expectations of the product development team, in turn driving their motivation (or lack thereof) to rely on FEA.

The case studies also demonstrated the observable influence that exposing product development teams to real applications of FEA can have on have on their design thinking and their confidence in FEA itself. This suggests that future efforts aimed at diffusing the use of FEA could be effectively built around such an approach. The study findings also offer hope that many of the commonly-cited barriers to the adoption of FEA can in fact be addressed and overcome through targeted diffusion efforts.

A final contribution of this work is the research method itself, which utilized a creative—if not unconventional—combination of established methods to investigate a topic of interest in its real-life context. The method, findings, and implications are offered to the design research community in the spirit of reflective research described by Schön (1983; quoted in Section 5.2) and research at the intersection of design practice and design theory described by Cross.

> The whole point of doing research is to extract reliable knowledge from either the natural or artificial world, and to make that knowledge available to others in re-usable form. This does not mean that works of design practice must be wholly excluded from design research, but it does mean that, to qualify as research, there must be reflection by the practitioner on the work, and the communication of some re-usable results from that reflection.
>
> Cross (2007, p. 126)

9.6 Limitations and Applicability

Several aspects of this research that make it unique are also tied its most significant limitations. Much of this was discussed in Section 5.8 and revolves around the reliance on an individual, embedded researcher, which amplifies the potential for researcher bias. In general, the use of multiple investigators is preferred, as it tends to strengthen the findings and generate more divergent perspectives of the data (Eisenhardt, 1989). An important mitigation to this was the use of a team of experienced interviewers to conduct the interviews with the case study participants.

The four established metrics for assessing the quality of empirical social research—construct validity, internal validity, external validity, and reliability—were examined in Section 5.8.1, along with the corresponding measures taken to enhance the overall quality of this research. Examples of such measures include the examination of rival hypotheses for the findings and the use of member-checking, the results of which were reviewed in the discussions at the end of each respective case study (Sections 6.4 and 7.4).

This research examined and drew conclusions from two case studies, which differed conveniently in terms of the nature of the design task, the role of the researcher, and the case study participants. However, two cases represents the minimum necessary for replication of important case study findings. A multiple-case investigation with a more complete set of theoretically-sampled cases would be beneficial for enriching and extending the validity of the proposed Confidence Model.

This research was scoped to address the perceptions of FEA in product development at Sandia National Laboratories, where the context assessment and case studies were conducted. As such, the findings are most directly applicable to Sandia. The similarity of the case study team compositions to that of the larger Sandia pre- and post-Context Assessment Surveys, as described in Sections 6.1.2 and 7.1.2, strongly support the applicability of these findings across the Sandia product development community. Beyond that, it is possible that the findings are the result of idiosyncrasies at Sandia National Laboratories and are not applicable elsewhere.

Despite this potential limitation, one positive aspect of this investigation is that it involved actual product development teams working on real projects at an established research and development (R&D) institution. This contrasts with a large portion of present design research, which is more commonly conducted using student teams in university course settings. In general, this should help the findings from this design research stand out in terms of its applicability to companies and other R&D institutions in industry.

The implications of this research may well extend to any organization that desires to increase the impact of FEA technology in the area of product design and development. For example, the results could be helpful to any company or institution that uses FEA in their product development processes, yet struggles to consistently achieve the desired level of buy-in from their product development teams. Alternatively, these results may provide insight for the community of FEA users or software developers desiring an increased influence and integration of their tools into product design.

Additionally, while this investigation focused specifically on FEA, the findings may in fact offer descriptive insight for enhancing the utilization and impact of other engineering simulation tools in the product development process, such as computational fluid dynamics (CFD), electrical and electronics simulation, and multi-physics simulation.

9.7 Future Research

Several ideas for future research on designerly FEA as a vehicle to address resistance to FEA in product development flow immediately from the limitations of the present work. First and foremost, subsequent investigations could be used to broaden the base of theoretically-sampled case studies, in order to further replicate or refute these findings. This in itself represents a significant undertaking, as several major investigational lines would be worthy of attention. These include targeting different types of FEA and levels of complexity (e.g., stress, thermal, non-linear), different classes of products (i.e., beyond the present focus on ruggedized electronics), companies in different sectors of industry (e.g., automotive, aerospace, consumer products, etc.), and companies of various sizes (e.g., large, established corporations versus small technology startups).

Another avenue for future research would be to test the ability of the proposed Confidence Model to explain both negative and positive perceptions of FEA. Such an investigation could be qualitative in nature and employ a pattern-matching strategy as described by Yin (2009). Several variations of this technique exist, but in essence it relies on applying a theory to a variety of cases to see if it accurately predicts observations, in order to strengthen the internal validity of the theory. A benefit of this strategy is that it could be conducted fairly easily using one-on-one interviews or survey tools, treating individuals as the 'cases'. This would forego the complexities of framing entire design projects as the case, and would also not necessarily need to involve the commitment of a longitudinal study.

Such an approach possess yet another benefit, in that it could be conducted by investigators that were not themselves members of the product development teams. This could be leveraged to eliminate the participant-observer element of the present work, which in and of itself may be a worthwhile idea for future research, in order to clearly demonstrate whether or not the present findings can be replicated when this potential source of researcher bias is removed.

An altogether different approach for future work would be to follow up this theory-building research with a quantitative investigation designed to establish statistically-significant correlations between several of the important factors that have been identified.

The topic of confidence in simulation technologies such as FEA may find synergy with other areas of investigation. For example, an emerging line of research at Stanford University's Center for Design Research (CDR) revolves around human-robot relationships. The idea is that if a technology is digital and programmable, it is essentially a robot; as a robot, it lacks an emotional response; and since it lacks an emotional response, humans have difficulty relating to and 'trusting' the technology (Leifer, 2015). This overarching view may offer insights in a variety of fields—ranging from consumer electronics to autonomous cars to simulation tools such as FEA—in which a 'human-robot team' exists. In such situations, human-robot relationships and the associated 'trust' issues are of central importance.

Finally, the results of this research offer guidance for designing future diffusion efforts aimed at extending the utilization and impact of FEA in product development activities. The Confidence Model suggests specific areas that should be focused on to maximize buy-in at the level of both individuals and teams. Direct comparison of FEA results and experimental test data, using FEA to guide design decisions and enhance overall design confidence, and ensuring that FEA activities are properly scoped to be completed within the allotted timeframe are particularly essential factors at securing and maintaining the confidence of design teams. The person performing the FEA must also possess—or be able to obtain—the team's confidence, so facilitating measures such as co-location and/or an integrated role on the product development team should be considered. Alternatively, future efforts might rely on a teaching approach in which a change agent guides others in using FEA, rather than the demonstration strategy that was employed in the present research.

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Appendices

Appendices A and B include the Sandia Context Assessment Survey (CAS) and the coding scheme that was developed for the short-answer questions.

Appendices C and D contain the text of the guided interview protocols. Appendices E and F summarize the concept inventories as they evolved over the course of data collection and analysis for each case study. Appendices G and H catalog the NVivo Framework Matrix summaries for each case study. Appendix I contains the Stanford Institutional Review Board (IRB) and Sandia Human Studies Board (HSB) applications and approvals for human studies aspect of the case study research, as well as the participant consent form required by the Sandia HSB.

Appendix J presents a more detailed overview of the particular type of FEA vibration and shock analyses performed in the case studies. Appendices K and L summarize additional details and various performance metrics for the FEA models.

Appendix A: Context Assessment Survey (CAS)

The following survey was conducted using Qualtrics online survey software (www.qualtrics.com).

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1. What is your technical background or degree field? (Select all that apply.)

    - Business administration
    - Computer science
    - Electrical engineering
    - Manufacturing engineering
    - Mechanical engineering
    - Other (please specify):

2. How long have you worked at Sandia (or your current employer)? (Select one.)

    - 5 years or less
    - 6 to 10 years
    - 11 to 15 years
    - 16 to 20 years
    - 21 to 25 years
    - 26 years or more

3. What is your present role at Sandia? (Select all that apply.)

    - Department manager
    - Electrical engineer
    - Manufacturing engineer
    - Mechanical engineer
    - Program management
    - Project/team leader
    - Quality assurance
    - Systems engineer
    - Other (please specify):

Finite element analysis (FEA) is also referred to as modeling or simulation. Some examples of its application include the following:

- Stress analysis (e.g., to see if a part will fail mechanically)
- Thermal analysis (e.g., to predict temperature distributions in a system, such as the example shown at right)
- Structural dynamics (e.g., to predict performance in vibration environments)
- Large deformation analysis (e.g., to predict how parts will deform in an impact environment)

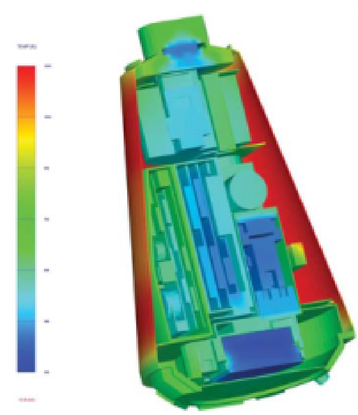

Image source: National Nuclear Security Administration Office of the Deputy Administrator for Defense Programs, "Defense Programs Strategic Vision for 2030," DOE/NA-0011 Publications, http://www.sandia.gov/ASC/pubs-media/pubs/dp-stratvision-2030.pdf

4. Have you ever seen FEA used on your past projects? (Yes/No.)

5. Have you ever used FEA software? (Yes/No.)
6. Have you ever taken a course on FEA? (Yes/No.)
7. Have you ever seen the use of FEA be beneficial to a project? (Yes/No.)
8. Have you ever seen FEA used in a way that was not beneficial, or perhaps even a hindrance, to a project? (Yes/No.)
9. What areas of a project have you seen affected by the use of FEA? (Select all that apply.)
    - Funding allocation
    - Product design
    - Qualification or testing methodology
    - Requirements development
    - Schedule planning
    - Other (please describe):
10. How have you seen the use of FEA be beneficial to a project? (Write-in short answer.)
11. How have you seen the use of FEA fail to benefit (or even hinder) a project? (Write-in short answer.)
12. (Optional) Please describe any factors that you think have an effect (positive or negative) on the value or usefulness of FEA results. (Write-in short answer.)
13. Do you ever participate in discussions or decisions that affect the mechanical design of a product? (Yes/No.)
14. Have you ever seen FEA results presented that did not seem trustworthy or accurate? (Yes/No.)
15. Have you ever seen FEA results that were not explained in a way that was clear and meaningful? (Yes/No.)

    For the following questions, let's define your "engineering intuition" to be your "gut feel" about a technical question, such as whether a design or product is likely to meet a specific performance requirement.
16. For mechanical design issues, what factors most influence your own engineering intuition? (Select all that apply.)
    - Expert advice from experienced engineers
    - Laboratory testing and/or experimental data
    - Results of analysis/calculations
    - Similarity to previous designs
    - Other (please describe):
17. How would you describe your thought process for weighing FEA results against other factors, or against your own engineering intuition? (Write-in short answer.)
18. What factors tend to affect your impression of the credibility of FEA results? (Write-in short answer.)

19. Please describe any factors that you feel are important for ensuring that FEA results are clear and meaningful for a product design team. (Write-in short answer.)
20. Have you ever seen the use of FEA be integrated with design activities? (Yes/No.)
21. Have you ever seen FEA used early on in the design process (for example, before design concepts are developed in full detail and before hardware prototypes exist)? (Yes/No.)
22. Have you ever seen FEA used in isolation from design activities (for example, due to limited communication, or because design activities had already ceased)? (Yes/No.)
23. What are the advantages and/or disadvantages of integrating design activities and the use of FEA? (Write-in short answer.)
24. What are the advantages and/or disadvantages of performing design activities and FEA in isolation from each other? (Write-in short answer.)
25. Does the use of FEA tend to lead, keep pace with, or lag design activities and decisions? Please describe. (Write-in short answer.)
26. In your opinion, how valuable is the use of FEA early on in the design process, and why? (Write-in short answer.)
27. Have you ever been involved in deciding whether or not to use FEA as part of a product design or analysis effort? (Yes/No.)
28. Have you ever seen the cost of using FEA be a factor in deciding whether or not to use it? (Yes/No.)
29. Have you ever seen the time required to utilize FEA be a factor in deciding whether or not to use it? (Yes/No.)
30. Please describe the factors that you feel contribute to the high cost of using FEA. (Write-in short answer.)
31. Please describe the factors that you feel contribute to the length of time required to use FEA. (Write-in short answer.)
32. (Optional) Please describe any thoughts you have on how project planning efforts can best address the use of FEA. (Write-in short answer.)

Appendix B: Context Assessment Survey (CAS) Coding

The following coding scheme, grouped into eight main categories, was developed in response to respondents' comments in the short-answer questions of the Sandia Context Assessment Survey (CAS).

Testing

- Complements experimental testing
- Design of experiments guided by FEA
- Diagnose test failures and understand test results
- Testing and-or design-test iterations can be reduced using FEA
- Testing required for model or results validation

Complexity

- FEA often unnecessarily complicated
- Real problems often too complex, too ill-defined, require too many assumptions
- FEA needed for complex designs, structures, systems
- Results too uncertain, sensitive, not accurate, or not trustworthy
- Skill or credibility of FEA analyst, expert-dependent

Dollar Cost

- Assess scenarios that are too expensive to test experimentally
- Dollar cost can be reduced using FEA
- Dollar cost too high using FEA

Time

- Early identification of issues and guiding subsequent design activities
- FEA typ. keeps pace, esp. later on when design concept is stable
- FEA typ. lags, esp. early when design concept is changing
- FEA typ. leads design activities
- Time can be saved using FEA
- Time required for FEA is too long

Integration

- Expectations, deliverables, scope for FEA must be clarified
- FEA analyst's knowledge of design details, project needs, audience
- FEA loses influence, applicability when isolated from design, test
- Fidelity of FEA and BCs vs design geometry and loads
- Goals must be aligned with design and project needs
- Isolation enhances independent verification, thinking, creativity
- Integration of FEA and design software

Communication

- Clear presentation of FEA results
- Communication about limitations, assumptions, details, esp. between design and FEA

Advantages/Disadvantages

- Analyzing systems to define sub-component requirements
- Improve or optimize product design, guide design decisions
- Weak points can be identified and analyzed
- Improperly used, poor assumptions, led team in wrong direction

Design Thinking

- FEA often determines something design engineers already know
- Use engineering judgment to view FEA
- Use FEA to inform engineering judgment or scope design problem

Appendix C: FEA Interview Protocol 1

The following guided interview protocol was used by the Stanford Center for Design Research (CDR) interviewers when conducting the first round of interviews with case study participants. Customized questions for each participant were generated using the coded responses shown in the tables at the end of the protocol.

FEA Interview Guide – 1st Round
Jerrod Peterson
Version 2012-07-23

Interviewer: [interviewer]
Interviewee: [number]
Interview date: [date]

Introduction

[Introduce yourself to interviewee]. I'm a [describe role] at Stanford and I've agreed to help Jerrod with this part of his research. Thanks again for being willing to participate in this online interview. I'll be asking you some questions that are similar to those you saw in Jerrod's online FEA survey, and I may ask you about some of your survey responses. Other questions will be new altogether. The interview will probably take around 30-60 minutes and covers about 15 questions. You'll probably have thoughts on some questions but not on others – so it's okay to say "I'm not sure" to any of them.

1. Before we begin, I just wanted to remind you of a few things.
    a. First, remember to keep all of your responses completely unclassified. Please don't discuss information that is classified or official use only.
    b. Second, I would ask that you refrain from discussing your responses with other team members, in order to ensure that their privacy is respected.
    c. Finally, remember that the audio and video from our call is being recorded. Is that still OK with you?
    d. *(If yes)* Okay, great. Do you have any questions for me before we begin? Okay, then let's get started.

First project

Today I want to ask you questions about two product development efforts you've recently been involved with. Let's start with the first project. My understanding is that the team has been working in earnest on this first project for a little under a year, and has recently built a first lab prototype and performed vibration and shock testing on it. Do you know which design project I'm referring to? Okay, great. Let's focus on that project for a while.

2. Do you think the use of FEA was beneficial for this project?
    a. *(If yes, and if prompting is needed for discussion)* Can you describe any beneficial impacts that you saw?

   b. In the FEA survey, you listed one of the benefits of FEA is that [benefit]. Did you see that at all on this project?
   c. Did the use of FEA seem to impact… *(probe for examples if they say 'yes' to these)*
      i. The design concept selected, or the final design of the product?
      ii. The development of requirements – for example, for sub-components?
      iii. The qualification method or the design of the test setup?
      iv. The overall understanding of how the design behaves mechanically?
3. On the FEA survey, you described a concern that [assumption]. Did you see anything on this project that either supported your view, or made you see things differently?
   a. Did any of the FEA results on this project seem not accurate or not clear? *(If yes)* Can you describe any of the questions or concerns you had about the results?
   b. On the FEA survey, you mentioned that [concern]. To what extent was that a factor on this project?
   c. Many people cited issues involving the need for improved communication about FEA results. For example, in your survey, you mentioned that [communication]. Did it feel like this, or any other communication issues, were a factor on this project?
   d. Are there any other issues that could be addressed to help make FEA more beneficial to a project like this one?
4. In the FEA survey, you indicated that on previous projects, you've seen FEA used for [previous]. Was this project the first time you've seen FEA used for vibration and shock modeling?
   a. Were there any similarities or differences between the use of FEA on this project, and past uses of FEA that you've encountered?
   b. What did you learn about FEA in the course of this project?

We're about 1/3 of the way through the interview. The next several questions are about using FEA in the design process.

5. For this project, can you give any examples of how the use of FEA was well-integrated into the design process?
   a. Can you give any examples of any disconnects or isolation you observed between the design process and the use of FEA?
   b. In the FEA survey, you mentioned that [time]. Did you see anything on this project that either supported your view, or made you see things differently?
6. How much of a factor was the cost (dollars) of using FEA on this project?
7. When it came time to perform vibration and shock testing on the design prototype, how confident were you that it would function or behave as intended?
   a. *(If prompting is necessary)* Can you name any factors that influenced your confidence?
   b. *(If more prompting is necessary)* For example, was your confidence influenced by… *(probe for examples if they say 'yes' to these)*
      i. The similarity of the design to existing products?

ii. The results of the FEA calculations?
iii. Any input or guidance you received from experienced engineers?

8. In the FEA survey, you stated that [testing]. Did you see that at all on this project?
9. In the FEA survey, you mentioned that [knowledge]. Did you see anything on this project that either supported your view, or made you see things differently?
10. How much is the use of FEA to answer mechanical design questions a part of your own design thinking process? As a result of this project, has FEA become more a part of your design thinking process, or less, or about the same as before the project?

We're almost finished discussing the first project. For the next few questions, I would ask that you give your answer on a scale of '1' to '10'.

11. Prior to this project, how would you have rated the feasibility of using FEA within resource constraints on a project like this one? Let's say '1' indicates using FEA was "not feasible at all" and '10' indicates using FEA was "perfectly feasible."
    a. Now let's fast-forward to the present, after completing one iteration of designing, building, and testing a laboratory prototype. Would you say your feasibility rating of using FEA on a project like this is about the same, or greater than, or less than before the project? *(Prompt for 'why' if no explanation given)*
12. Prior to this project, how would you have rated the use of FEA as a legitimate engineering approach? Let's say '1' indicates FEA was "not legitimate at all" and '10' indicates FEA was "fully legitimate."
    a. Now let's fast-forward to the present again. Would you say your legitimacy rating for using FEA is about the same, or greater than, or less than before the project? *(Prompt for 'why' if no explanation given)*
13. On the FEA survey, you indicated that your background is [background]. Prior to this project, how important was it to you personally to have an understanding of FEA? Let's say '1' indicates understanding FEA was "not important at all" to you, and '10' indicates understanding FEA was "extremely important" to you.
    a. Now let's fast-forward to the present again. Would you say the importance to you personally of understanding FEA is about the same, or greater than, or less than before the project? *(Prompt for 'why' if no explanation given)*

Second project

Okay, at this point we're about 3/4 of the way through the interview. I'd like to conclude by briefly discussing the second of the two product development efforts that you've recently been involved with. My understanding is that the team has been working in earnest on this second project for a little under a year, and has put a lot of effort into documenting design requirements, and recently held an early conceptual design review, but that as of yet no prototypes have been built or tested. Do you know which design project I'm referring to? Okay, great. I have a few questions for you regarding this project. And again, remember, if you need to say "I'm not sure" to any of these, that's okay.

14. Based on what you observed or learned on the first project, in what ways do you think the use of FEA is most likely to be beneficial on this second project?
    a. Can you think of something that is important to you, in your role, that FEA might be able to provide information on? *(If they can't think of anything, that's okay… this is meant to stretch their thinking)*
15. What factors might limit the effectiveness of using FEA on this particular project?
    a. *(If this is not mentioned)* Do you foresee any issues in terms of the credibility of the FEA results?
    b. *(If this is not mentioned)* Do you foresee any issues in terms of FEA keeping pace with design activities on this project?
    c. Based on what you observed or learned on the first project, can you offer any suggestions on how this second project can best utilize FEA in the design process?
    d. Can you think of one critical question you might ask about any FEA model results that are obtained on the second project? *(If they can't think of anything, that's okay… this is meant to stretch their thinking)*

Conclusion

16. Okay, that's the end of my question list. But before we conclude, do you have any other thoughts that we haven't covered today?
17. Okay, that's it. Thanks again for sharing your thoughts and experiences with us.

Participant	[benefit] – typical benefits
No. 1	It can provide additional design insight
No. 2	It can reveal design flaws
No. 4	It can help make design decisions and can reveal design weaknesses
No. 5	(Omit)
No. 6	It can reduce the chance of needing a redesign
No. 7	It can help get a design in the right ballpark when calculations are not doable by hand
No. 8	(Omit)
No. 9	It is helpful for basic design guidance and for developing a deeper understanding of the design
No. 11	(Omit)

Participant	[assumption] – assumptions, limitations, and interpretation
No. 1	The application of FEA requires intuition and judgment
No. 2	(Omit)
No. 4	When test results and FEA disagree, it's important to understand why
No. 5	(Omit)
No. 6	(Omit)
No. 7	FEA results can be very sensitive to small errors and assumptions

Participant	[assumption] – assumptions, limitations, and interpretation
No. 8	(Omit)
No. 9	The FEA analyst must understand the broad context and the physical product or situation they are modeling
No. 11	(Omit)

Participant	[concern] – general concerns
No. 1	FEA can result in a hit to the project budget
No. 2	FEA must begin with geometry that is reliable
No. 4	(Omit)
No. 5	(Omit)
No. 6	(Omit)
No. 7	Sometimes FEA is done just for the sake of doing it, without adding value
No. 8	(Omit)
No. 9	Sometimes FEA is done with external motives and does not directly benefit the project
No. 11	(Omit)

Participant	[communication] – communication issues
No. 1	(Omit)
No. 2	In general, it can be difficult to relate engineering results to others who aren't fluent
No. 4	(Omit)
No. 5	(Omit)
No. 6	(Omit)
No. 7	FEA model details should be disclosed and retrievable
No. 8	(Omit)
No. 9	The analyst should explain why they believe the FEA model
No. 11	(Omit)

Participant	[previous] – previous uses of FEA
No. 1	(Omit)
No. 2	Stress analysis
No. 4	(Omit)
No. 5	Thermal analysis
No. 6	Thermal analysis
No. 7	Aerodynamics modeling
No. 8	(Omit)
No. 9	(Omit)
No. 11	(Omit)

Participant	[time] – integration, early use, and isolation with respect to design process
No. 1	FEA can be used early to guide design decisions
No. 2	FEA is often used to solve problems after the design is complete, so it lags the design process
No. 4	It's difficult for FEA to keep pace with the design process

Participant	[time] – integration, early use, and isolation with respect to design process
No. 5	FEA is most useful when it keeps pace with the design process
No. 6	FEA is most useful when it keeps in pace with design activities
No. 7	(Omit)
No. 8	(Omit)
No. 9	It's good when information can be obtained quickly from FEA
No. 11	(Omit)

Participant	[testing] – proper relationship to testing
No. 1	FEA can be beneficial in the design of testing, and for extrapolating from test results
No. 2	(Omit)
No. 4	(Omit)
No. 5	(Omit)
No. 6	(Omit)
No. 7	FEA should be coupled with testing, and can actually reduce the chance of needing to retest
No. 8	(Omit)
No. 9	It's good when FEA is used to augment a physical test program
No. 11	(Omit)

Participant	[knowledge] – FEA results vs. other sources of knowledge
No. 1	FEA can be used to test your own judgment
No. 2	FEA can function as a sort of "independent verification"
No. 4	You don't necessarily place more value on either test results or simulation results
No. 5	FEA is more analytical than relying on engineering intuition only
No. 6	(Omit)
No. 7	FEA can be used to understand problems seen in testing
No. 8	(Omit)
No. 9	(Omit)
No. 11	(Omit)

Participant	[background] – background
No. 1	Electrical engineering
No. 2	Electrical engineering
No. 4	Electrical engineering
No. 5	Electrical engineering
No. 6	Electrical engineering
No. 7	Mechanical engineering
No. 8	Aerospace engineering and business administration
No. 9	Mechanical engineering
No. 11	Electrical engineering

Appendix D: FEA Interview Protocol 2

The following guided interview protocol was used by the Stanford Center for Design Research (CDR) interviewers when conducting the second round of interviews with case study participants. Customized questions for each participant were generated using the coded responses shown in the tables at the end of the protocol.

FEA Interview Guide – 2nd Round
Jerrod Peterson
Version 2013-09-06

Interviewer: [interviewer]
Interviewee: [number]
Interview date: [date]

Introduction

[Introduce yourself to interviewee]. I'm a [describe role] at Stanford and I've agreed to help Jerrod with this part of his research. Thanks again for being willing to participate in this online interview. I'll be asking you some questions that are similar to those you saw in the first round of interviews, and I may ask you about some of your previous responses. Other questions will be new altogether. The interview will probably take around 20-30 minutes and covers about 15 questions. You'll probably have thoughts on some questions but not on others – so it's okay to say "I'm not sure" to any of them.

Before we begin, I just wanted to remind you of a few things.

I. First, remember to keep all of your responses completely unclassified. Please don't discuss information that is classified or official use only.
II. Second, I would ask that you refrain from discussing your responses with other team members, in order to ensure that their privacy is respected.
III. Finally, remember that the audio and video from our call is being recorded. Is that still OK with you?
IV. *(If yes)* Okay, great. Do you have any questions for me before we begin? Okay, then let's get started.

Questions

Today I want to ask you some questions about a product development effort you've recently been involved with. My understanding is that the team has been working on the mechanical design for a little over a year and the earliest electrical prototypes were started about 9 months ago. Also, a first prototype of the design went through vibration and shock testing in April and thermal testing in June. Do you know which design project I'm referring to? Okay, great. I'm going to call this 'Project No. 2' to be consistent with the last round of interviews, but almost all of these questions are going to focus on this project.

1. From your perspective, did it seem like the use of FEA was integrated with the design process for this project?

2. To what extent did the FEA influence your confidence or engineering judgment about the design?
3. In Project No. 1, which was discussed at length in the first round of interviews, many people said they had confidence the design would do well in vibration testing because of its similarity to a previous design. For this project, was design similarity a factor for you?
4. Jerrod did a lot of the mechanical design work on this project, but he also did the vibration FEA modeling. How did that affect your view of each (the product design itself, and the FEA)?
5. From what I understand, you did vibration testing on the first prototype, and used data from that testing to compare to the vibration FEA model. Similarly, you did thermal testing on the first prototype, and used data from that testing to compare to the thermal FEA model. Did you notice any advantages or disadvantages to this method of combining FEA and testing?
6. For this question, let's imagine a future project where there was funding to cover someone whose full-time job was to perform FEA modeling for the product development team.
    a. What factors would be important to you in terms of building your confidence in the FEA results, and also in terms of helping the FEA results to have a real impact in the design process?
    b. In the first interview, you mentioned that the credibility of the FEA results [credibility]. Did you see anything that confirmed that view, or made you see things differently?

At this point, we're about 1/3 of the way through the interview. The next set of questions is about your perceptions of FEA.

7. On a scale of 1 to 10, with 10 being the highest, how would you rate FEA in terms of being a legitimate engineering approach?
    a. Has your confidence in FEA either increased or decreased as a result of this project?
8. On this project, were there instances where the limitations of FEA were especially evident to you, or where the assumptions in the FEA model seemed problematic?
    a. In the first interview, you mentioned that a critical question you would ask about the FEA results is [critical question]. Did you see anything interesting in this regard?
9. On a scale of 1 to 10, how beneficial overall do you feel the use of FEA was for this project?
    a. In the first interview, you said that on this project, FEA might be beneficial [potential benefit]. Did you see that at all?
    b. You also said that the effectiveness of FEA might be limited [potential limitations]. Was that a factor at all on this project?
    c. From your perspective, if you had to identify one factor that prevents FEA from being even more beneficial, what would it be?
10. On a scale of 1 to 10, how would you rate the feasibility of using FEA on a project like this one?

11. Let's discuss the idea of feasibility a little more. In the first round of interviews, nearly everyone mentioned something about the amount of time that it can take to develop FEA models.
    a. For example, you [keeping pace]. Did anything on this project either support that view, or make you see things differently?
    b. Do you think FEA was able to keep up with the project?

Okay, now we're about 2/3 of the way through the interview.

12. From your perspective, to what extent was the dollar cost of using FEA an issue?
13. What was your impression of the accuracy of the FEA results on this project?
14. Can you think of any ways to improve communication about FEA results amongst the members of the product development team?
15. Jerrod noted that you suggested some other possible uses for FEA on this project. For example, [original application]. This is neat, because it shows that FEA is part of your thought process.
    a. So my question is, for you, what is it that makes FEA come to mind when you're thinking about a design problem?
    b. Have you thought of any others uses for FEA since then?
    c. In the first interview, we asked if there was something important to you, in your role, that FEA might be able to help with. You said that [important factor]. Do you think FEA was helpful at all for this?

For these last few questions, let's imagine a time in the future where everyone on this product development team has moved on separately to new projects. So you are they only member of the current team that has now moved on to some new project that you're working on.

16. Are there any ways that you would definitely want to see FEA used, or NOT used, on this future project?
17. Do you have any ideas about how to take things that have been learned about FEA on these two projects, and leverage that forward into this future project?
18. Based on everything we've discussed today, and in all honesty, do you think you would be more likely to be skeptical of using FEA on this future project, since it takes time and has limitations, or would you be more likely to be an advocate of using FEA?

Conclusion

Okay, that's the end of my question list. But before we conclude, do you have any other thoughts that we haven't covered today? Okay, that's it. Thanks again for sharing your thoughts and experiences with us.

Participant	[credibility] – something that might impact credibility of FEA
No. 1	Should not be an issue, because we were not trying to extrapolate the FEA results beyond what we're seeing with our testing.

Participant	[credibility] – something that might impact credibility of FEA
No. 4	Might be affected if they're unable to spend enough time fine-tuning the model.
No. 7	(Omit)
No. 8	Should not be an issue -- that the first project proved we are getting results we can use, and that the FEA was really only for our own internal reassurance about the design.
No. 11	Might be affected if they are hugely different than the test data.
No. 12	[IN THE FEA SURVEY] Might be affected if they don't seem realistic compared to simplified calculations.
No. 13	(Omit)

Participant	[critical question] – critical questions they would ask of the FEA results
No. 1	(Omit)
No. 4	What is the fidelity of the model? Do the test results match the simulations? And do you understand the differences?
No. 7	Can show that your FEA model predicts some test result with reasonable accuracy? Because if not, a lot of confidence in the model is lost.
No. 8	If the FEA and test data for the first project agree well enough, can we reduce testing and rely more directly on the FEA for the second project?
No. 11	Were any major weaknesses identified, and how does the model compare to the test results?
No. 12	[IN THE FEA SURVEY] Details about assumptions, boundary conditions, joints and contacts, and uncertainty.
No. 13	(Omit)

Participant	[potential benefit] – things FEA might be beneficial for on this project
No. 1	Because there's value in getting familiar with FEA, developing a process for using it, and understanding the time and effort required.
No. 4	For helping to make early design decisions and design trade-offs.
No. 7	If we setup the FEA model early, perform experimental testing of first the prototype, use that data to validate the model, and then use the model to help with design decisions.
No. 8	For figuring out early on what's going to work and what's not going to work -- which should speed up the project and also build confidence in the design early in the process.
No. 11	For giving the team greater confidence in their design, and possibly for pointing out design flaws.
No. 12	[IN THE FEA SURVEY] For predicting what might occur during testing, or for predicting potential failure locations.
No. 13	(Omit)

Participant	[potential limitations] – factors that might limit the effectiveness of FEA
No. 1	If the models get to the point that Jerrod cannot run them on his PC, and you instead need to go to the supercomputers.
No. 4	By time and budget, because the schedule is pretty tight.
No. 7	By time, because the schedule is so tight, and possibly also by accuracy limitations due the design complexity.
No. 8	Because of late-changing requirements, but then you thought perhaps FEA could actually help address late-changing requirements.
No. 11	If the design is extremely similar to other designs that have already been tested, then FEA might be unnecessary and might not impact design confidence.
No. 12	[IN THE FEA SURVEY] If poor assumptions are made about things like convergence of the FEA model, or boundary conditions.
No. 13	(Omit)

Participant	[keeping pace] – comments on whether or not FEA would keep pace with design
No. 1	Thought that time shouldn't be too much of a problem, but you said it would depend on making sure Jerrod did not get overloaded, due to all his various roles.
No. 4	Said it was possible that FEA would have trouble keeping pace with design activities.
No. 7	(Omit)
No. 8	(Omit)
No. 11	For example, you said that time could be a limitation, since making the FEA models seems to take longer than the normal design activities.
No. 12	[IN THE FEA SURVEY] For example, you said that most of the design work is complete based on quick analysis, whereas many times the FEA is done afterward to see the overall result.
No. 13	(Omit)

Participant	[original application] – ideas for using FEA that they proposed on their own
No. 1	On multiple occasions on this project. Here are some examples of what you suggested: using FEA to estimate the vibration and shock levels that various sub-components would see; using FEA to look at thermal issues; and placing certain components at different locations in the overall system, rather than inside your electronics assembly.

Participant	[original application] – ideas for using FEA that they proposed on their own
No. 4	When the team was deciding whether to have any kind of additional support underneath the center of the stack of circuit boards. The options were either some large electrical components called DC-to-DC converters, or a bracket with a pad, or just not having any additional support. You suggested that FEA might be able to help decide if any of these options affected the vibration and shock levels at the circuit boards.
No. 7	(Omit)
No. 8	(Omit)
No. 11	(Omit)
No. 12	(Omit)
No. 13	(Omit)

Participant	[important factor] – something important to them that FEA might help with
No. 1	(Omit)
No. 4	It’s helpful to understand the vibration and shock levels that the circuit boards would see.
No. 7	It might be helpful for answering quick questions on the design. You mentioned some specific examples: where and how to mount components, vibration and shock levels they would see, designing brackets and parts, and making 'relative' comparisons of design options.
No. 8	Having confidence early in the design is important, because it allows for an aggressive schedule and might even help reduce the number of tests we need to perform.
No. 11	It is important to identify weak links in the design.
No. 12	[IN THE FEA SURVEY] FEA could be valuable, if it is done well and done correctly, because it can potentially spot flaws in the design.
No. 13	(Omit)

Appendix E: Case Study 1 Concept Inventory

The evolution of concepts included in the first case study data collection and coding is summarized below.

	Time →		
	Initial concepts	**Added concepts based on FEA survey results and field notes**	**Added/dropped concepts based on 1st FEA interview results and field notes**
Included concepts	• Benefits • Hindrance • Product design impacts • Accuracy • Clear / meaningful • Engineering intuition • Credibility • Design similarity • Early use in design process • Integration with design process • Isolation from design • Time required • Dollar cost	• Confidence in design • Communication • Relation to laboratory testing • Assumptions and limitations • Design understanding • Feasibility • Legitimate • Opinions on appropriate use • Conceiving of new applications • New things learned • Desire to understand FEA • View as learning process • Likely to carry FEA forward	• General role of FEA analyst • Particular role of investigator-participant • Confidence in FEA • Misconceptions
Dropped concepts	N/A	• Credibility	• Hindrance • Clear / meaningful • Engineering intuition • Early use in design process • Legitimate

Appendix F: Case Study 2 Concept Inventory

The evolution of concepts included in the second case study data collection and coding is summarized below.

	Time →		
	Initial concepts	**Added/dropped concepts based on 1st FEA interview results and field notes**	**Added/dropped concepts based on 2nd FEA interview results and field notes**
Included concepts	• Benefits • Product design impacts • Accuracy • Credibility • Design similarity • Integration with design process • Isolation from design • Time required • Dollar cost • Confidence in design • Communication • Relation to laboratory testing • Assumptions and limitations • Design understanding • Feasibility • Opinions on appropriate use • Conceiving of new applications • New things learned • Desire to understand FEA • View as learning process • Likely to carry FEA forward	• General role of FEA analyst • Particular role of investigator-participant • Confidence in FEA • Misconceptions	• Exemplar of FEA • Intersection with other sources of design knowledge
Dropped concepts	N/A	• Hindrance • Clear / meaningful • Engineering intuition • Early use in design process • Legitimate	• New things learned • Misconceptions • Isolation from design • Desire to understand FEA

Appendix G: Case Study 1 Framework Matrix Summaries

The following tables are taken from the NVivo Framework Matrix for the first case study and present summaries of the coded case study data (survey, interview, and field notes).

Participant	Product design impacts
No. 1	No indication of having previously seen FEA impact product design -- although, initially indicated that "FEA or advanced analysis techniques should be used early on to decide design… directions." On this project, did not cite any specific product design impacts.
No. 2	Previously, had seen FEA impact product design, such as by revealing design flaws. Did not observe any such direct impacts on product design for this project, due to strong reliance on design similarity. However, noted that, in general, FEA "does provide another way to make design decisions."
No. 4	Previously, had seen FEA impact product design, such as by revealing potential weaknesses in the design, and also stated that "FEA should help make design decisions." On this project, indicated that was used to model a couple different designs, which helped make the final design selection.
No. 5	Previously, had seen FEA impact product design. On this project, noted that FEA was used to assess a couple different design options, but seemed to indicate that actual impact was minimal since FEA was used "in parallel" with committing to the baseline design concept.
No. 6	Previously, had seen FEA impact product design. At the end of this project, noted that FEA was used to "sort of 'prove' that [the selected] design is better than the other types." Also noted that FEA can be useful for design trades within the design team, stating "As a benefit to an electrical engineer, that's… I think it's more beneficial to mechanical engineers, in a way, because they have to choose the design, but as far as electrical, it gives me more confidence that if Jerrod wants to add a screw and take away my board space, it's perfectly fine with me, you know what I mean? It's a valid concern."
No. 7	Previously, had seen FEA impact product design, and used as a guideline to get the design in the right ballpark, mostly qualitatively, when calculations were not doable by hand. On this project, did not provide any specific impacts on product design, but rather described two instances of the use of FEA to help confirm design decisions.
No. 8	No indication of having previously seen FEA impact product design. Likewise, on this project, no specific impacts of FEA on product design were recalled, and indicated that it was due to their limited role in selecting the final design.

Participant	Product design impacts
No. 9	Previously, had seen FEA impact product design, and emphasized the value of using FEA to "help guide design choices." On this project, noted that FEA "informed" and "put tangible numbers behind" early design decisions, but further elaborated that design decisions were essentially made, and that FEA was used to help confirm those decisions.
No. 11	No indication of having previously seen FEA impact product design. On this project, noted that FEA was used to assess different design concepts, and may have been a factor in helping to narrow down the final design, but seemed unsure of whether FEA had any actual impacts beyond this, such as revealing design flaws.

Participant	Integration with design process
No. 1	Initially, remarked that FEA should be used early -- to guide design, to guide test methods -- and that it should lead or keep pace with design activities. On the one hand, indicated initially that they had seen FEA integrated with design activities, and used even before hardware prototypes exist, but at the end of the project, reflected on past experiences, stating "we need to change how we think about the design process, and start looking at these other tools that are out there." Regarding the use of FEA on this project, stated that "it's an integrated part of our team, it's integrated into our design process."
No. 2	Previously, had not seen the use of FEA be integrated with design activities, but instead had only seen FEA used to solve problems long after design work was complete. Stated, in other words, that people have not necessarily "looked at [FEA] as a design tool." Recognized that here we are using it earlier in the design process, and feels that is the right thing to do.
No. 4	Previously, had seen FEA integrated with design activities, but not to the extent of using FEA early on in the design process, before concepts are fully detailed or before hardware prototypes exist. Remarked, initially, that it seemed like "it would be difficult for FEA to keep pace with design activities." On this project, seemed to view FEA as fairly well-integrated with design activities, citing the use of FEA to help make decisions and gain confidence in design changes. Even so, at the project conclusion, seemed to maintain a view of the challenge, stating that "the biggest challenge with FEA keeping up with the design process is just trying to fine-tune the model as you go along."
No. 5	Previously, had not seen FEA integrated with design activities. In this project, seemed to hold a view that FEA was used in a beneficial manner, although described the use of FEA as being in parallel with the rest of the design process. In other words, a design decision was

Participant	Integration with design process
	made, and FEA was used to assess that selection in parallel with committing to the selected design. Seems to be implying that FEA was well-integrated with the overall product development process, but not as much with the 'design' portion of that overall process.
No. 6	Previously, had seen FEA integrated with design activities, but not to the extent of using FEA early on in the design process, before concepts are fully detailed or before hardware prototypes exist. Noted that, when used alongside the design process, FEA can "ensure the validity of the design and reduce the chance redesign." On this project, described the primary benefit of FEA as providing understanding about performance of the design prior to going to testing, which helps reduce the chance of product failure and redesign. But, felt that the analysis was still a little too late and a little too close to testing.
No. 7	Previously, had seen FEA be integrated with design activities, but not used early on in the design process, before prototypes exist. Indicated that they had mainly seen FEA lag the design process, sometimes used "just as an exercise in doing it, with little value added to the overall project." On this project, noted that FEA was used early in the design process to predict the vibration/shock levels that an already-designed part would see when installed in the new design. And, that FEA was used to assess whether small design changes should require re-testing.
No. 8	No data on initial view. Noted that on this project, FEA seemed to provide value early on in the design process, which was unexpected. Also noted that as a result of this project, FEA has become more a part of their design thinking process, mainly in that now the person is aware to plan for the use of FEA.
No. 9	Previously, had seen FEA be integrated and even used early in the design process. However, cited various causes for poor integration in the past: goals for analysis do not align with goals for design/project group, and poor partnering/communication between analyst and design engineer. On this project, the use of FEA "was completely integrated because Jerrod was a core member of the product team, and so, you know, he brought this to the table as one of his deliverables for the team."
No. 11	No data on initial view. On this project, noted that FEA was used to evaluate different design concepts. Believes (but not sure) that FEA was used to help narrow down final design selection. At the end of the project, when asked about the feasibility of using FEA within resource constraints on a project like this one, connected it to the idea of integration in the design process. Reflecting back to the beginning of the project, viewed FEA as moderately feasible (giving it a rating of '4' on a scale of 1 to 10). By the end of the project, viewed

Participant	Integration with design process
	FEA as more feasible, "because I saw that they could do it within the design process and help -- use it to help guide decisions."

Participant	Design understanding
No. 1	Initially, remarked that "the big advantage [of integrating design activities and the use of FEA] is that when FEA is used correctly, the potential for added insight into a design can be tremendous." Noted that FEA seemed to help the mechanical engineers on this project better understand the mechanical design. Also reflected on the overall process, remarking that "when you start looking at budget constraints, when you start looking at how requirements are being levied on us, then we need to change how we think about the design process, and start looking at these other tools that are out there, other than simply doing things the way we've always done them before, which is, in some cases, over-design, which increases cost to a project, in some cases it may be harder to actually meet some of the requirements because you've overdesigned, yet then you don't have a feel for where you can change your design to meet other requirements but still meet, say, your shock and vibration environments."
No. 2	No data on any initial view of how FEA can assist with design understanding. At the conclusion of the project, never gave any indication that the understanding of the design was enhanced by the use of FEA.
No. 4	No data on any initial view of how FEA can assist with design understanding. By the conclusion of this project, observed that "We typically test our products with vibe and shock testing, and the way we test, you really don't know how much margin you have - it's kind of a pass/fail test. So you know it either passed or it didn't, you don't know how rugged your design really is. And so the FEA allowed us to be able see kind of what amplitudes and levels we're seeing at different locations." Discussed this application of FEA more than once in the interview -- seemed really interested in it.
No. 5	No data on any initial view of how FEA can assist with design understanding. By the conclusion of this project, did view FEA as having an impact on the overall understanding of how the design behaves mechanically, specifically citing the agreement between FEA and test results as evidence. Also stated that by utilizing FEA, "as you get further down the road, you're really going to understand exactly how the hardware is working."
No. 6	Initially, described a previous exposure to the use of FEA for thermal analysis, in which FEA was used to determine if an electrical circuit board component that was selected for the design was working beyond its junction temperature range. On this project,

Participant	Design understanding
	specifically stated that one of the beneficial impacts of using FEA was that it "was able to show us the predicted behavior of the hardware before it went to testing," and that its very interesting to see the effect of small details in the design, "so we can understand what exactly is in the mechanical design that is affecting certain things, certain behaviors."
No. 7	No substantial data on any initial view of how FEA can assist with design understanding. On this project, noted that FEA revealed how our internal components react to the external vibration and shock loading. Stated that FEA is becoming more a part of their design thinking, although presently uses FEA only for more specific questions (i.e., simpler analyses).
No. 8	No data on any initial view of how FEA can assist with design understanding. By the end of this project, indicated that FEA did seem to impact the overall understanding of how the design behaves mechanically, specifically noting that the FEA "seemed to inspire confidence in the mechanical and electrical engineers."
No. 9	Initially, did describe a "better understanding of [the] design and possible issues" as a benefit of utilizing FEA in the design process. Confirmed that FEA was beneficial in a likewise manner on this project. Also described how FEA results and test results were both used to understand what elements of the design affect vibration and shock results.
No. 11	No data on any initial view of how FEA can assist with design understanding. Regarding this project, stated without any elaboration that it did seem like FEA was helpful in this regard.

Participant	Confidence in design
No. 1	In the past, had seen FEA used prior to testing to confirm whether the design would perform acceptably in the required field conditions. Also selected analysis as an influential factor in their engineering judgment. However, for this project, never really described the use of FEA as contributing specifically to "confidence" in the design.
No. 2	Did not cite examples of FEA being used in the past to provide confidence in design decisions. In fact, stated that had not really seen FEA used in the design phase of product development. Did not select analysis as an influential factor in their engineering judgment. On this project, did make a general comment that FEA "does help to have another way to make design decisions." But specifically regarding this project, remarked that confidence in the product prior to testing was not based on FEA calculations, but rather on the strong similarity to a previous design.
No. 4	Initially, selected analysis as an influential factor in

Participant	Confidence in design
	their engineering judgment. On the FEA survey, mentioned three times that FEA was used on this project to understand the risk associated with a specific design change that was necessary.
No. 5	Initially, selected analysis as an influential factor in their engineering judgment. On this project, commented numerous times on the use of FEA to confirm decisions and add to our confidence. Remarked, "you know, the engineering judgment is great - you know, I think it really helps us make some decisions early - but I think typically that's going to be the first step, and your second step is going to be to go and perform some sort of analysis on what your engineering judgment was. I think they can be joined, but I think you can't really have one without the other. You can't start the process without engineering judgment, and you can't prove your engineering judgment without some sort of analysis."
No. 6	Initially, did NOT select analysis as an influential factor in their engineering judgment. On this project, remarked at least three times the FEA results affected confidence in the design that was selected, i.e., that the design would perform acceptably during hardware testing.
No. 7	Initially, did select analysis as an influential factor in their engineering judgment. Had seen FEA used "as a guideline for design to get us in the right ballpark, mostly qualitatively." Regarding this project, remarked several times that FEA was used to "confirm" the design decision that was made. "There was kind of like one or two or three different paths we could have gone down on, and the FEA sort of confirmed that the path we were going down was okay. I don't think it necessarily led us down that path, because we were led down that path for other reasons. But I guess it made us more confident that that was a good path to go down."
No. 8	No data on initial view of how FEA affects confidence in design decisions. Regarding this project, identified this as essentially the biggest impact of FEA: allowing the team to develop confidence early in their design, so that an aggressive schedule could be proposed and maintained. "From my vantage point, it was all about gaining confidence. Because Jerrod was able to do this modeling early, it allowed for very aggressive scheduling… It's all about confidence in what we have as a conceptual design: is it going to work." For this person, FEA did improve their confidence, but overall deferred to mechanical engineers, who likewise seemed confident.
No. 9	Initially, did select analysis as an influential factor in their engineering judgment, noting that FEA can help guide design choices and ensure adequate design margin. On this project, overall theme of remarks was that FEA confirmed our design decisions and assumptions, adding quantifiable results to back up engineering judgment.

Participant	Confidence in design
	Used the words "confidence" or "confident" xx times during the course of the first interview.
No. 11	No data on initial view of how FEA affects confidence in design decisions. On this project, described an improved confidence level as the main benefit of using FEA, although also commented that FEA results had less of an impact on overall confidence than other factors (engineering judgment, design similarity to existing products).

Participant	Laboratory testing
No. 1	Previous experience seemed to hinge around the idea that FEA is used to guide testing (design of test setup, test methodology), with testing in turn being the ultimate source from which design confidence is gained. Described previous exposure to the interplay between modeling, testing, and using test data to refine model, and wants to see that implemented in our design process. Interestingly, noted that engineering judgment is important for interpreting both experimental and modeling results, and pointed out the possibility that test results, too, can be incorrect, and like FEA results, must be viewed with a healthy sense of engineering judgment about what the expected answer/measurement should be.
No. 2	Initially, indicated that has seen FEA affect qualification or testing methodology. Only elaboration on that was that in the past, has only seen FEA used after design was long done. On this project, noted the benefit and importance of directly comparing FEA results to test results. Over the course of this project, no real changes in views are observable, although there is perhaps an emerging view: "It’s sure a lot easier to run tests with computer simulation, rather than actual hardware… maybe you don’t have to go through so many iterations when you’re designing."
No. 4	Initially, noted on the one hand that laboratory testing has the biggest impact on their engineering judgment, but that if calculations and test data don't agree, "you need to understand why they differ and base decisions on that. I don't automatically place more value on one or the other." On this project, noted that "One thing that surprised me was that the FEA results were directly comparable to our vibe and shock data. You could really put them side by side and do a direct comparison. So that was interesting." No evidence of a change in previous views; stated that since "FEA results are dependent on your fidelity… my opinion would be that you wouldn’t rely solely on the simulation results. You always need to run actual tests." Observed that FEA results serve as a strong complement to our test data: "We could probe around different locations in the system

Participant	Laboratory testing
	and effectively ‘instrument’ the system in places that we couldn’t instrument in actual hardware… It’s difficult to have accelerometers and sensors everywhere on the boards, and on the hardware, and so the FEA allowed us to see - probe around and see - what environments we were seeing at different locations that we couldn’t actually measure."
No. 5	Initially, had seen FEA impact testing methodology, and indicated that testing had the biggest impact on engineering intuition. Later reflected on this view, stating that, "I walked in thinking, 'yeah, analysis is great, but it's on the side.'" On this project, felt that analysis and testing complemented each other, and now feels that we should always make an effort to match test results via analysis. Elaborated that, "Going back to that whole ‘analysis versus testing,’ I’ve always been on the end of, 'let’s go test it out.' But when you come into the real world, and you’re working with hard deadlines, you don’t always get that luxury to really test… Then I started to really look at the results, and I really looked at, early in the design, what he was doing, and it felt like, it should be a part of every project. Like, it made me… no matter what, I think even if you do have the time to test, you should match your analysis with your testing."
No. 6	Initially, indicated that analysis "can reduce the chance of redesign/rework on finished product," but beyond that, did not articulate views on the relationship of FEA to lab testing. By the conclusion of the project, cited as a main benefit of FEA the fact that it "was able to show us the predicted behavior of the hardware before it went to testing," and that because of this, "it can definitely reduce the chance for a redesign." Specifically mentioned the comparison of the FEA data to the test data as important and impactful.
No. 7	Previously, identified lab testing as having the most influence on their engineering intuition. Had observed, based on past encounters with FEA where access to testing resources was limited, that "some kind of testing to go along with the FEA model, or at least parts of it, is necessary, especially for a more complex system." On this project, observed that testing was leveraged to collect data for validating FEA model. Also remarked, "I'm starting to think of more ways something like this could be integrated into answering quick questions on the design -- not necessarily before or instead of testing, but in addition to testing."
No. 8	No initial data on their view of the relationship between FEA and lab testing. On this project, seemed to view the main benefit of FEA as building early confidence that a design will perform as intended during actual testing, to help minimize chances of needing a redesign/rebuild, so that more aggressive schedules can

Participant	Laboratory testing
	be executed.
No. 9	In the past, had seen FEA impacting testing methodology, and stated that "it is good when FEA is used to augment a physical test program." Also, had seen people not understand the cost of validating a model, and later wished they had just gone straight to testing. On this project, observed an interplay between test results and analysis results that led to a better understanding of both the design itself (what features matter), and how to model the design. Notably, described two extremes that are to be avoided: "At one end, it would be, 'Oh, we need modeling and simulation on every project, or every product, we do.' And then the other extreme would be, 'Oh, it buys us nothing. We have to test anyhow, so why should I invest money in that?'"
No. 11	No substantial evidence for this person either for previous views or views on this project. Did not really comment at all on the relationship between testing and FEA. Noted that on future projects, credibility of FEA would be negatively impacted if test data revealed that FEA was not at all accurate.

Participant	Design similarity
No. 1	Initially, did NOT indicate that design similarity was a factor in their engineering intuition. Likewise, on this project, indicated that similarity to previous design was a small factor in overall confidence. Did not elaborate or comment on this at length, as did several other participants.
No. 2	No data on an initial view of the influence of design similarity. On this project, noted that FEA did not have much impact on the design since it was a modification of an existing design. Due to strong similarity to previous design, impact of FEA on this person's thinking appears to have been minimal.
No. 4	Initially, DID indicate that design similarity was a factor in their engineering intuition. For this project, noted several times that a lot of their confidence was due to the similarity to a previous design, but also noted several times that FEA helped provide confidence in the required design changes.
No. 5	Initially, DID indicated that design similarity was a factor in their engineering intuition. Likewise, on this project, cited confidence due to the fact that "we weren't doing a complete redesign, and a completely new technique. It was just a modification of something that we've done before. So that gave me stronger confidence."
No. 6	No data on an initial view of the influence of design similarity. On this project, cited design similarity as a basis for confidence, stating that "because of the similarity between the two - the existing product and this project… it certainly gave me confidence. It's not

Participant	Design similarity
	brand new - it's not something that nobody has ever seen."
No. 7	Initially, DID indicate that design similarity was a factor in their engineering intuition. On this project, specifically cited design similarity, stating that, "for me, at least, the confidence wasn't necessarily based on the FEA, it was kind of based on similarities to previous designs."
No. 8	No data on an initial view of the influence of design similarity. On this project, cited design similarity helping their confidence "a little bit."
No. 9	Initially, DID indicate that design similarity was a factor in their engineering intuition. On this project, mentioned design similarity as a factor in their confidence, stating that, "my confidence really is derived from [the team] and from knowing that this product wasn't hugely dissimilar from other things we have done."
No. 11	No data on an initial view of the influence of design similarity. On this project, did indicated that design similarity was a factor in their confidence.

Participant	Role of research investigator
No. 1	Initially, DID indicate that advice from experienced engineers is a factor in their engineering intuition. On this project, did refer to my familiarity with the previous design from having worked on it several years ago.
No. 2	No data on an initial view of the influence of advice from experienced engineers. On this project, cited my experience on the previous design as a factor, but seemed to describe it as secondary to the influence of the design similarity itself.
No. 4	Initially, DID indicate that advice from experienced engineers is a factor in their engineering intuition. On this project, did cite my experience with the previous design -- alongside the similarity of the design itself -- as a factor in their confidence.
No. 5	Initially, DID indicate that advice from experienced engineers is a factor in their engineering intuition. On this project, did mention my experience, but did not tie it specifically to the previous design, and essentially stated that it was not a major factor on this project.
No. 6	No data on an initial view of the influence of advice from experienced engineers. On this project, when discussing my role on the previous design and the similarity of the design itself, stating that "because of the similarity between the two - the existing product and this project - and especially Jerrod's involvement in the previous design… yeah, it certainly gave me confidence." So perhaps slightly more credit is being given to my previous role.

Participant	Role of research investigator
No. 7	Initially, DID indicate that advice from experienced engineers is a factor in their engineering intuition. On this project, when discussing my role on the previous design and the similarity of the design itself, remarked that "It's hard to say whether the confidence came from the engineers, necessarily, or the design itself, because they're kind of one in the same." An interesting remark.
No. 8	No data on an initial view of the influence of advice from experienced engineers. On this project, did not cite my role on the previous design as having an impact on confidence.
No. 9	Initially, DID indicate that advice from experienced engineers is a factor in their engineering intuition. On this project, cited the overall experience level of the team, as well as my specific experience with the previous version of this product, as a factor in their confidence.
No. 11	No data on an initial view of the influence of advice from experienced engineers. On this project, drew an apparent tie between my experience on the previous version of this product, and the similarity of the design. In any case, appears to indicate that my role on the previous design was a factor in their confidence.

Participant	Beneficial overall
No. 1	Previously, had seen FEA be beneficial, and had not seen FEA be a hindrance. Cited the use of FEA to gain additional design insight and to guide test methodology as benefits. Likewise, on this project, felt that FEA was beneficial. Noted specifically that it is a good fit for our industry since we do custom designs with extremely low-volume production. Also noted that "whether you have to make [design] changes or not, [FEA] still gives you better insight into what is happening with the design," which can in turn be applied to future designs. Overall, no change on view of the benefits of FEA, but rather, state that this project "has not changed my opinion of FEA, I think it's reinforced… my opinion [that it's] a good and useful tool."
No. 2	Previously, had seen FEA be beneficial, and had not seen FEA be a hindrance. Cited the use of FEA to solve a stress problem. On this project, stated that they believed FEA was beneficial, but expressed being involved only indirectly. Overall, not a strong sense of conviction in the response.
No. 4	Previously, had seen FEA be beneficial, and had not seen FEA be a hindrance. Cited the use of FEA in revealing a potential design weakness. On this project, indicated that FEA was beneficial "for the most part." Commented on how FEA can provide additional information beyond what can be gained in testing, such as design margin

Participant	Beneficial overall
	(since most testing is pass/fail) and acceleration levels at other points that are not instrumented in testing.
No. 5	Previously, had seen FEA be beneficial, and had not seen FEA be a hindrance. Cited the use of FEA to analyze the impact of a required welding operation in terms of the heat that would be induced in adjacent electrical components. On this project, stated that FEA was beneficial, specifically noting how FEA was used in parallel to assess the design as it was being developed.
No. 6	Previously, had seen FEA be beneficial, and had not seen FEA be a hindrance. Cited the use of FEA thermal analysis to assess whether an electrical component was working beyond its junction temperature. On this project, stated that FEA was beneficial, specifically noting that FEA "was able to show us the predicted behavior of the hardware before it went to testing," and that the validity of the model was confirmed by the strong agreement between the FEA and test results.
No. 7	Previously, had seen FEA be beneficial, citing the use of FEA as a guideline to get a design "in the right ballpark" when calculations "were not doable by hand." But, had also seen times when FEA was a hindrance, citing one instance in which FEA was done "an exercise in doing it" and "add no value to the overall project," and another instance when an assigned FEA task "turned out just to be busy work and the parts I was doing analysis on were already in production." On this project, felt that FEA was beneficial, stating that "there are a couple instances where I do think it helped." Also remarked, "Originally, I thought this was kind of a lot of work to put into it, because we were getting kind of one thing out of it at the beginning. But I think of it more as a kind of proof-of-concept for this project now."
No. 8	No data on previous experiences with FEA being either beneficial or a hindrance. On this project, felt that FEA was beneficial, describing the benefit as that of giving the mechanical design team confidence early in the design, which enabled putting forth a very aggressive schedule that was so far being held.
No. 9	Previously, had seen FEA be beneficial, citing the use of FEA to provide "basic design guidance" of various sorts. But, had also seen times when FEA was a hindrance, citing several examples, e.g., poor alignment between project needs and the goals of the analysis, poor communication between engineer and analyst, poor understanding of the ability of the model to predict complicated nonlinear behavior, or poor understanding of the amount of testing that would be required to validate a complicated model. On this project, indicated that FEA was beneficial, describing that although "I don’t think [FEA] brought to light things that they didn’t know," it was used to confirm and provide more credibility to the

Participant	Beneficial overall
	team's design decisions.
No. 11	No data on previous experiences with FEA being either beneficial or a hindrance. On this project, when asked if FEA was beneficial, indicated, "I think so, yeah," noting that FEA gave the team confidence in their design.

Participant	Assumptions and limitations
No. 1	At the beginning of the project, remarked that "intuition and judgment really applies to how far one stretches the FEA data." Likewise, throughout the interview, commented on the importance of understanding the capabilities and limitations of FEA. Stated, "If you don’t have an idea somewhere of the direction that you’re going with the modeling, and what you think should be the right answer, then the modeling I think can… what would it be… it’s almost 'garbage in, garbage out' so-to-speak. If you don’t have an idea of what the right answer should be, then you’re not going to know what it’s telling you. You need to know something about what your system is doing, and how it responds, and so that’s where I think this intuition, and early “back of the envelope” calculations - whatever you want to call it - need to be there to better understand what the FEA is telling you." Also remarked, "It’s not a panacea, it will not answer all of the questions," but we need to "understand its limitations and its advantages."
No. 2	No indication of any initial views on the assumptions and limitations inherent in FEA models. Likewise, not much discussion of any assumptions or limitations of the FEA modeling for this project. However, when thinking forward to FEA modeling of the second case study project, did make the interesting observation that while electrical cables are a potential failure point, they are difficult to capture in an FEA model.
No. 4	No indication of any initial views on the assumptions and limitations inherent in FEA models. By the conclusion of the project, discussed some key trade-offs at length. For example, observed that "you have to trade-off between which features you want to model and keeping the model simple, so that it’s a quick simulation. So trying to figure out which features are necessary and which features aren’t seemed like a challenge." Also noticed that "it seemed difficult to figure out which features were critical to having a high-fidelity model and which features weren’t."
No. 5	No indication of any initial views on the assumptions and limitations inherent in FEA models. Likewise, not much discussion of any assumptions or limitations of the FEA modeling for this project. However, when thinking forward to FEA modeling of the second case study project, did make the interesting observation that the

Participant	Assumptions and limitations
	vibration and shock requirements for this product were not yet well defined, which could be an issue for doing the FEA modeling.
No. 6	No indication of any initial views on the assumptions and limitations inherent in FEA models. At the end of the project, reflected back and stated that, "I assumed before…that you plug in a few parameters, and the software would have… algorithms that calculate everything for you." But instead, observed that between modeling the components and putting in assumptions, "it's like the number of parameters is way beyond what I thought." Also, when thinking ahead to the FEA modeling on the second case study project, noted that "every engineer might model things differently."
No. 7	At the beginning of the project, remarked that "many small errors / bad assumptions could creep in and greatly skew the results." Also, described the possibility of a bad model driving bad design decisions, or product specifications that have been derived from a system model without also passing along information about the conditions, assumptions, etc. to the component engineer. On this project, observed two examples that confirmed this view (i.e., sensitivity of results to assumptions). But also noted two instances where the lack of sensitivity to certain assumptions was surprising. So the project seemed to partially substantiate, but also partially refute, this person's inclination to distrust FEA results.
No. 8	No real evidence of views/awareness of FEA assumptions at either the beginning or end of this project.
No. 9	At the beginning of the project, already had a high awareness of how assumptions can affect FEA results, specifically noting that it is important for an analyst to be able to "explain the assumptions they made and the effects they had on the results." After presentation of the initial FEA results of the 3 design concepts, commented that they liked the clear description of what the FEA is and is not telling us -- specifically the slide with the big red "X" through it. Likewise, at the conclusion of the project, noted the importance of being aware of assumptions that were being made, e.g., boundary conditions, simplifications, etc. Also, regarding the FEA model for this project, this person encouraged me to contact a mutual colleague for guidance on how to optimally determine what model parameters are most responsible for disparities between FEA and test data.
No. 11	No real evidence of views/awareness of FEA assumptions at either the beginning or end of this project.

Participant	Confidence in FEA
No. 1	Reflecting back to the beginning of the project, viewed

Participant	Confidence in FEA
	FEA as a highly legitimate engineering approach (giving it a rating of '10' on a scale of 1 to 10), and echoed that view at the conclusion of the project. Never expressed any lack of confidence in FEA per se, but repeatedly emphasized the importance of understanding the limitations and assumptions involved in an FEA model.
No. 2	Reflecting back to the beginning of the project, viewed FEA as a moderately legitimate engineering approach (giving it a '5 or 6' on a scale of 1 to 10), stating that, "in a perfect world, you'd like to say it was a '10,' but models aren't quite perfect yet, and that's a really hard thing to do -- to get a good model." At the end of the project, seemed to maintain the same overall moderate level of confidence in FEA as a legitimate engineering approach. Connected the idea of confidence in FEA as a legitimate engineering approach to confidence in the analyst performing the FEA.
No. 4	Reflecting back to the beginning of the project, viewed FEA as a moderately legitimate engineering approach (rating it "5" on a scale of 1 to 10), noting that "I hadn't had any previous experience with it." By the end of the project, seems to have gained some improved confidence in FEA, indicating an increase to "a 6 or 7." Connected the idea of confidence in FEA as a legitimate engineering approach to having sufficient time to utilize FEA, stating, "I think it's worth the time, but it's hard to get that time when you're on a fast-paced project."
No. 5	Reflecting back to the beginning of the project, viewed FEA as a moderately legitimate engineering approach (rating it "6" on a scale of 1 to 10), noting their "limited experience" with it. By the end of the project, indicated a "much greater" view of the legitimacy of FEA, noting, "Initially I was just very much in my electrical engineering world, and I didn’t use FEA, and so… and I just didn’t have confidence in it… And so I think really, this project really changed my opinion of how critical it is to perform that analysis." Regarding confidence in FEA models, also stated, "no matter what, I think even if you do have the time to test, you should match your analysis with your testing. And with that, you can build confidence in your models."
No. 6	Reflecting back to the beginning of the project, viewed FEA as a moderately legitimate engineering approach (rating it a "6 or 7" on a scale of 1 to 10). At the conclusion, viewed FEA as slightly more legitimate, stating, "in my future designs, I would certainly put it under my consideration… because of the confidence that Jerrod has built for the first project." However, noted that "legitimate" and "useful" are two different things, and that initially, did not think FEA was that useful. Emphasized the importance of building confidence in FEA techniques, stating, "I think this is important for FEA

Participant	Confidence in FEA
	engineers, is that they have to be able to establish this confidence in this analysis in programs, because if they don't, all their work is practically wasted, right? Because you do something, you present it, people look at it, no comments, and you stop and you move on. So the model is never carried through. So every time you start a new FEA project, you kind of have to start over, you know what I mean? You kind of have to carry it all the way. You have no chance of improving your model because nobody cares."
No. 7	Initially, commented that "I think some kind of testing to go along with the FEA model, or at least parts of it, is necessary, especially for a more complex system. Once part of the FEA model is valid, adjustments can be made with more confidence." Reflecting back to the beginning of the project, viewed FEA as a highly legitimate engineering approach (rating it a '9' on a scale of 1 to 10). At the conclusion of the project, maintained the same view of FEA. "I'm not questioning its legitimacy at all. It's kind of like anything -- you get what you put in. So if you put legitimate work into it, I think you'll get legitimate things out." Did remark that they now view this application of FEA as "a kind of proof-of-concept," seeming to imply that some confidence was gained in FEA over the course of the project.
No. 8	Reflecting back to the beginning of the project, viewed FEA as a highly legitimate engineering approach (rating it a '9' on a scale of 1 to 10), commenting that although "I always thought it was hard, and sometimes probably not necessary, but… I would definitely say it's legitimate -- I've seen it work before." At the conclusion of the project, maintained this same view of FEA. Other than this, no real substantial comments directed at confidence in FEA itself.
No. 9	Initially, described a variety of factors that affect their impression of the credibility of FEA results, but they were primarily focused on agreement of FEA results with intuition, familiarity with the analyst, the analyst's ability to communicate, and explanation of assumptions and their affects. Reflecting back to the beginning of the project, viewed FEA as a very legitimate engineering approach (rating it a '8' on a scale of 1 to 10). At the conclusion of the project, maintained the same view of FEA. Other than this, no real substantial comments directed at confidence in FEA itself.
No. 11	Reflecting back to the beginning of the project, initially viewed FEA as a moderately legitimate engineering approach (rating it a '5' on a scale of 1 to 10). At the conclusion, indicated that they viewed FEA as "a little bit" more legitimate, as a result of seeing FEA "used in a positive way." But no other really sub-stantial comments focused on confidence in FEA itself.

Participant	The analyst
No. 1	Repeatedly numerous times during interview a view that for this type of design work and FEA, the person doing the analysis should be part of the design team. Mentioned specifics including being part of the same organization, a member of the design team, co-location with the design team, and having the same project leader. Described numerous benefits to this approach including an overall improvement in communication, reduced time to perform analysis and obtain results, improved working with electrical engineers, and cost savings. Suggests that expert analysts from other groups perhaps best suited for much larger and/or complicated problems than our design projects. Says this project "reinforced" this overall view. Mentions an initial desire to have an FEA capability "in-house," and a push to have me be part of this project due to my interest/ability in using FEA. Taken together, suggests this view was held initially and reinforced over the course of the project.
No. 2	In describing their view of legitimacy of FEA, described how someone with "better knowledge and experience" is able over time to refine FEA models based on test results, thus improving the overall legitimacy of FEA as an engineering approach. "And part of that is who you've got doing it. I think people's experience with it, and how they follow up with it… if I took Jerrod's comparison to some other folks, you know, I would definitely rely on Jerrod more than what I've seen some other folks do."
No. 4	Did not mention any influence that my role on the product design team (or my experience with the predecessor product) had on their views of the FEA for this product. Also did not articulate any views on ideal role/involvement of the person performing the FEA relative to the product design team.
No. 5	Did not mention any influence that my role on the product design team (or my experience with the predecessor product) had on their views of the FEA for this product. Also did not articulate any views on ideal role/involvement of the person performing the FEA relative to the product design team.
No. 6	Did not mention any influence that my role on the product design team (or my experience with the predecessor product) had on their views of the FEA for this product. Also did not articulate any views on ideal role/involvement of the person performing the FEA relative to the product design team.
No. 7	Did not mention any influence that my role on the product design team (or my experience with the predecessor product) had on their views of the FEA for this product. Also did not articulate any views on ideal role/involvement of the person performing the FEA relative to the product design team.
No. 8	No data on an initial view regarding this topic. At the

Participant	The analyst
	end of the project, was asked about their view of the feasibility of using FEA on projects like this. Remarked that although this project has shown it is feasible, "I would caveat that with saying you need the proper resources. You need someone like Jerrod to be able to do it." Not clear what it was about me or my role on the project that is being referred to.
No. 9	Initially, described how FEA results are more valuable/useful "when engineer and analyst work closely together" and "when good judgment determines when and how to best incorporate FEA (not driven by other motives)." Also, when asked to describe factors that affect the credibility of FEA results, recited a litany of questions focused almost exclusively on the analyst: "Do I know the analyst? Do other experts know the analyst? Trust the analyst? Can the analyst discuss the results in a broad context? Do they understand the physical product/situation they are modeling? Can they explain the assumptions they made and the effects they had on the results?" At the end of the project, when asked about the feasibility of using FEA within resource constraints on a project like this one, connected it at least in part to the idea of Reflecting back to the beginning of the project, initially viewed FEA as moderately feasible on a project like this despite resource constraints (giving it a rating of '4' on a scale of 1 to 10), but as a result of this project, and seeing FEA used from the beginning to the end of a design cycle, now sees FEA as more feasible (giving it a rating of 7) By the end of the project, elaborated on some of these same thoughts, specifically mentioning my familiarity with our products and the conditions they see, and my awareness of the effects of boundary conditions and other simplifications needed to model our products. Specifically mentioned my membership on the design team and co-location with the design team. Expressed a continuing appreciation for "how important experience is for the analyst." Overall, it seems this project has reinforced their initial views.
No. 11	Did not mention any influence that my role on the product design team (or my experience with the predecessor product) had on their views of the FEA for this product. Also did not articulate any views on ideal role/involvement of the person performing the FEA relative to the product design team.

Participant	New things learned
No. 1	Did not identify anything new that was learned about FEA over the course of the project.
No. 2	Did not really describe anything new that was learned about FEA per se, but did mention several times that using FEA early in the design process different from

Participant	New things learned
	previous uses they had seen in which FEA was used to troubleshoot problems with a product long after the design work was complete.
No. 4	Stated, "One thing that surprised me was that the FEA results were directly comparable to our vibe and shock data. You could really put them side by side and do a direct comparison. So that was interesting. And I did learn about how sensitive the FEA results are to the fidelity of the model. It's difficult to get your model just right, without it being too cumbersome and slow, simulation-wise."
No. 5	Mentioned several new things learned about FEA, including the amount of time required to use FEA, and the overall process of performing analysis, performing hardware tests, and then comparing results. Regarding the FEA and test results, remarked that "it was really good to see how much they are identical if you do it correctly."
No. 6	When asked what was learned about FEA over the course of the project, commented "That it's actually very hard work! I assumed before, based on the thermal analysis that I've seen, that you plug in a few parameters, and the software would have programs - algorithms - that calculates everything for you. But from what Jerrod described, it's like he actually had to model the components, put in his assumptions… it's like the number of parameters is way beyond what I thought. So, it's very complex, and I understand now why it takes so long, and why some projects wouldn't even bother doing this. It's very difficult."
No. 7	Seems to have learned several things about FEA over the course of this project. Indicated that previously was not really using or familiar with vibration/shock analysis. Remarked, "I was actually pretty surprised at how accurate he - Jerrod - got it, in the kind of qualitative sense. But a lot of the peaks of all the frequencies were close to where they actually were, and matched up with the test data, you know. And he didn't need a team of people working on a model for months to actually accomplish that. So that was kind of… I don't know if it was 'surprising,' but it was good to see that that's possible with even kind of - you know, not the kind of big, high end FEA software - but something we could do from our offices."
No. 8	Stated that "the biggest thing I've learned is that it seemed to provide some value early in the project, and I wasn't expecting that." Described how in previous encounters with FEA, had only ever seen FEA used to model a physical object that already existed, whereas here, we're modeling a design concept that has not yet been built.
No. 9	Previously, seems to only have seen vibration analysis attempted on even more complex systems. Conversely, had only seen FEA used for simpler analyses on our products.

Participant	New things learned
	Beyond this, did not describe anything new that was learned, but emphasized a continuing and deepened appreciation for the level of experience of the analyst.
No. 11	This was this person's first major introduction to FEA. Stated that this project "gave me an idea of what [FEA] is and what it's used for."

Participant	Misconceptions
No. 1	Under impression that I had response data on a predecessor design that I used as a basis for comparison for this FEA model, which was true only in a very limited sense. Test data from the predecessor design was used to try to estimate an appropriate damping level, but in the end, the data were so inconclusive that it was basically useless. Instead, I estimated the initial damping level of 3% by taking a damping level of 2% that I have observed in smaller, presumably less-damped systems, and increasing it slightly. The final damping level of 4% was established using the test data collected on this project.
No. 2	While discussing the process of comparing FEA results to test results, remarked that "it's sure a lot easier to run tests with computer simulation, rather than actual hardware." May indicate a misunderstanding about exactly what this type of FEA model is telling us, and to what extent it can replace hardware testing.
No. 4	Remarked that the FEA allowed us, prior to testing, to see if "we were on the verge of possibly breaking something or not." With such comments, it is always difficult to tell whether they have a good view of how much interpretation is required, particularly with the type of modal/vibration/shock analysis I am performing.
No. 5	Asked about using this same simplified type of modeling to assess failure/survivability of the sub-component that we are incorporating into this design. This person feels other users/customers of that component would be interested in some sort of a study of its overall robustness. I tried to explain that as far as predicting failure of the guts of the component itself, that is another type of analysis. But this person really seemed stuck on the idea that in some way, what I'm doing must be usable in this regard. Possibly a misconception about what the analysis is telling us -- or possibly a misconception on my part about the question(s) this person has in mind.
No. 6	During the interview, remarked that by using FEA, "if we had any concerns as far as breaking of the hardware before testing, we would have caught it." Statements like this may indicate a misunderstanding about what the FEA model is and is not telling us.
No. 7	No evidence of lingering misconceptions regarding FEA.
No. 8	Summarized a key benefit of FEA as follows: "It's all

Participant	Misconceptions
	about confidence in what we have as a conceptual design: is it going to work." May reflect a misconception about whether these analyses are telling us that a design will work (in an absolute sense), vs. indicating that one design option is more likely to work than another design option (in a relative sense). Also stated that, "What the FEA modeling in my mind has been able to do is when we come up these conceptual designs on where to put pieces, and how they fit together, if we have some idea of how they are going to respond in the shock and vibration testing and environments, before we actually build it, we can play with things: putting stuff different places, arranging boards differently, arranging where the cards and connectors are, and have some assurance that when we build it, we're not going to have to go tear it apart, redesign it, and rebuild it multiple times - putting it through tests and trying to bring it back. And so, by doing the analysis in the model, they were able to do that really quickly: moving stuff around, seeing how stuff fit together, getting some idea of how it would respond in the environment." These comments are not inaccurate in an outright sense, but suggest a possible misunderstanding about how thoroughly we can explore various design concepts, or how many concepts can be explored, or how quickly/easily the analyses can be performed.
No. 9	No evidence of lingering misconceptions regarding FEA.
No. 11	While discussing the use of FEA to reveal design flaws, commented that it wasn't clear if FEA actually revealed any design flaws on this project. So it seems like this person might still be trying to figure out whether this type of FEA can reveal design flaws, and if so, possibly what types of design flaws it can reveal.

Participant	Feasibility
No. 1	Reflecting back to the beginning of the project, viewed using FEA within resource constraints as highly feasible on a project like this (giving it a rating of '10' on a scale of 1 to 10), and echoed that view at the conclusion of the project. Never expressed any lack of confidence in the feasibility of using FEA on this project.
No. 2	Reflecting back to the beginning of the project, viewed using FEA within resource constraints as moderately feasible on a project like this (giving it a rating of '4' on a scale of 1 to 10). Specifically noted that this rating was in terms of using FEA 'up-front', as a 'design tool,' which was not how this person had seen FEA used in the past. As a result of this project, viewed the feasibility of using FEA on a project like this as greater, stating, "It's not up to a '10,' but you know, you're moving in the right direction."

Participant	Feasibility
No. 4	Reflecting back to the beginning of the project, viewed using FEA within resource constraints as moderately feasible on a project like this (giving it a rating of '5' on a scale of 1 to 10), and stated this rating was primarily due to a lack of experience with FEA. As a result of this project, viewed it as more feasible (giving it a '6' or '7), because "I can see the value in it. It does help the designers made decisions before, you know, actually cutting metal and having the parts made, and I can see the value in that."
No. 5	Reflecting back to the beginning of the project, viewed using FEA within resource constraints as moderately feasible on a project like this (giving it a rating of '5' on a scale of 1 to 10). As a result of this project, viewed it as much more feasible.
No. 6	Reflecting back to the beginning of the project, viewed using FEA within resource constraints as moderately feasible on a project like this (giving it a rating of '4' on a scale of 1 to 10), and stated that, "Just knowing how long it usually takes for FEA results to come out, and how fast we're going on this project, I didn't think it was really that feasible." As a result of this project, viewed FEA as much more feasible, because "he built a lot of confidence in me by correlating his results with the real world results, it definitely builds more confidence, and I think it's more feasible in the future knowing that this can be done."
No. 7	Reflecting back to the beginning of the project, viewed using FEA within resource constraints as moderately feasible on a project like this (giving it a rating of '5' on a scale of 1 to 10), and stated that this was "just because I don't have a lot of experience, and I wasn't sure, without spending months on it, how good of results we could get. But just looking at it now, I'm happy with the results we got from this initial FEA study, so now I see it as slightly more feasible."
No. 8	Reflecting back to the beginning of the project, initially viewed using FEA within resource constraints as moderately feasible on a project like this (giving it a rating of '4' on a scale of 1 to 10), and noted that "I was more concerned about the timeline than the ability to do it." As a result of this project, views FEA as much more feasible, noting, "it's been done -- it is feasible."
No. 9	Reflecting back to the beginning of the project, initially viewed using FEA within resource constraints as moderately feasible on a project like this (giving it a rating of '4' on a scale of 1 to 10). Commented that, typically, "I think what we would have done is used it for something specific. So, if we didn't know about a particular fitting, or a bolt, or a 'something,' we would have done it very small scale, and not the whole project." As a result of this project, views FEA as more feasible (giving it a rating of '7'), based on having

Participant	Feasibility
	seen the results from two iterations of the FEA used during the product design cycle.
No. 11	Reflecting back to the beginning of the project, initially viewed using FEA within resource constraints as moderately feasible on a project like this (giving it a rating of '4' on a scale of 1 to 10). As a result of this project, views FEA as more feasible, "because I saw they could do it within the design process and help -- use it to help guide decisions."

Participant	Isolation from design
No. 1	Previously, had not seen FEA used in isolation from design. On this project, did not cite any examples of disconnects or isolation between design and analysis.
No. 2	Previously, this person had seen FEA used in isolation from design -- in fact, this was the main way they had seen FEA used: to troubleshoot problems encountered during assembly/testing of products that were already designed. Interestingly, pointed out that one benefit of using FEA separate from design activities was that it can be used to perform an "independent verification of the design." On this project, did not cite any examples of disconnects or isolation between design and analysis.
No. 4	Previously, had not seen FEA used in isolation from design. On this project, did not cite any examples of disconnects or isolation between design and analysis.
No. 5	Previously, had not seen FEA used in isolation from design. On this project, commented repeatedly on how FEA was used to analyze various design concepts in parallel with making the design decision and moving forward. Remarked, "I think ultimately there was some disconnect in how well we could have really used Jerrod's analysis right away, because we pretty much made the decision. But Jerrod's analysis confirmed that our decision was correct."
No. 6	Data on previous experiences was mixed. On the one hand, indicated that they had not seen FEA used in isolation from design. But, mentioned and later elaborated on a previous experience in which a thermal FEA analysis was performed and took so long that by the time the results came in, the product had already successfully passed hardware qualification testing and was in production. Similarly, regarding this project, the data were somewhat mixed. Stated that "I don't think there was any isolation," but went on to describe the level/quality of communication about the FEA results back to the rest of the design team. On a different note, commented that "I think Jerrod was just - in my opinion - just slightly late in presenting his FEA results, sort of right before the testing… I sort of proceeded without knowing if there's any mechanical stuff I need to watch out for when I'm doing the [electrical] design." So regarding

Participant	Isolation from design
	both past experiences and this project, seems to be saying the FEA results need to be completed sooner.
No. 7	Previously, this person had seen FEA used in isolation from design. Described a project where they were tasked with doing some FEA, but "it turned out just to be busy work and the parts I was doing analysis on were already in production." Noted that one possible advantage of separation between design and analysis activities is that it "might catch things not caught in testing." Observed one problem with the FEA on this project that this person viewed as an example of something caused by isolation between design and analysis. Initial version of the FEA was performed with a measurement taken at a spot on the simulator component that likely was not consistent with how the original testing of that item was performed (during its original design and development). This is a very interesting and astute observation on this person's part -- it shows just how easily problems can creep into an analysis when the analysis is relying on the design work and/or testing performed by another person or organization.
No. 8	No data on this person's previous views/experiences on this topic. Regarding this project, did not cite any examples of disconnects or isolation between design and analysis, but also caveated that, pointing out their limited involvement in the actual design work.
No. 9	Data on previous experiences was mixed. On the one hand, indicated that they had not seen FEA used in isolation from design. But, did describe problems caused by poor alignment between the funding -- which often comes from the R&D side -- and the objectives of the product engineer, who needs a fairly quick indication of whether or not their part or design is going to work. On this project, did not cite any issues with disconnects or isolation between design and analysis.
No. 11	No data on this person's previous views/experiences on this topic. Regarding this project, did not cite any examples of disconnects or isolation between design and analysis.

Participant	Communication
No. 1	Previously, had not encountered instances where FEA results were not explained in a clear and meaningful way. Indicated that communication about FEA results was not an issue on this project. Remarked, "Because Jerrod… is just right down the hallway, and so it's very easy to keep a very close communication link going… If you've got somebody in another group… it makes it much harder to have daily contact to just go in and say, 'How are things going? What are the issues?' So I'm a big proponent of what Jerrod is doing and particularly with the fact that it is located within our own project.'

Participant	Communication
No. 2	At the beginning of the project, noted that "one of the basic problems with engineering results is the ability to relate them to others who aren't fluent." Interview recording broke up when this person was asked directly about communication on this project about FEA results, so their view of this is uncertain. In response to all other interview questions, did not describe any problems related to communication about FEA results on this project.
No. 4	Previously, had not encountered instances where FEA results were not explained in a clear and meaningful way. Indicated that communication about FEA results was not an issue on this project. Remarked, "Jerrod was pretty clear about caveats and other things, the issues that we were seeing. So, yeah, communication went very well."
No. 5	At the outset of the project, indicated that they had not encountered instances where FEA results were not explained in a clear and meaningful way. However, at the end of the project during the interview, described previous experiences where "I see a couple results pages, and they're great, and they're… they don't mean anything to me." (Could have been on another project mentioned in the interview, that is going on at the same time as this project and that is also using FEA.) Regarding communication on this project, remarked, "So on this particular project, Jerrod has been extremely good at providing results. His presentations that he gave were in depth - you know, exactly how something performed at specific frequencies for specific tests. I thought that in this case, it was extremely well documented."
No. 6	No data on initial views/experiences with communication about FEA results. On this project, commented, "He clearly explained his assumptions and exactly what he put into those models to have this. So he did a really good job explaining." Also described how "I'm not very familiar with looking at shock and vibe analysis," and how early on, their experience was "looking at the analysis and sort of not really understanding exactly how it affects the whole system. But it definitely… did when he mapped it to the actual testing." And also, "As far as how he presented his model results, and how well it correlated with the testing results, I don't think there was any disconnect in communication." So comparing analysis results directly to testing results seems to have been something of a universal language that helped this person better understand this topic, which was new for them.
No. 7	Had previously encountered instances where FEA results were not explained in a clear and meaningful way. Commented on the importance of being able to retrieve FEA results, stating, "I think just knowing something about the model is a good start. When we get specs, for

Participant	Communication
	example, sometimes they come from an FEA model I know nothing about and there doesn't seem to be a place where one could find that information." Also suggested that a "designer may not communicate correct assumptions to [the] party doing the FEA." At the end of the project, later elaborated on this point, stating, "I think the way the FEA results were presented was sufficient for most people… I feel like if I wanted to really delve into the details - I didn't at this point - but if I wanted to, I could ask Jerrod, basically, and get all the kind of nitty-gritty models and things. I never felt like he was hiding anything from us, I guess. That kind of was my concern in that survey - is that things could be manipulated or hidden. And I think a very good job was done on this project of kind of just laying it out there, and if something's off, you know, you just kind of say, 'it's off,' and don't try to sweep it under the rug."
No. 8	No data on initial views/experiences with communication about FEA results. On this project, succinctly remarked that "Everything that I was shown seemed very clear," and, "From my position… I got all the information I needed out of it."
No. 9	Had previously encountered instances where FEA results were not explained in a clear and meaningful way. Listed several factors that are important for ensuring that FEA results are clear and meaningful for a product design team: explaining the limitations of models, in units and terms relevant to engineers; explaining assumptions and impacts they have on results; and explaining why the model should be believed, e.g., test cases or previous cases run. Later elaborated on this, stating, "In some cases, the engineer would hand off to the analyst and say, 'Tell me if this is going to fail under these loads.' And then the engineer didn't keep a close relationship with the analyst to understand, you know, what direction was the analyst going? What assumptions were they building into the model? What data were they using for materials properties? The engineer just thought, 'I come back and I get the answer.' So again, it's the communication, and it's both ways." Regarding this project, felt that communication about FEA results "…was very well handled" as a result of Jerrod being "…in-tune… with trying to understand the communities on both sides, to bridge the gap. I think, with his team, he never tried to hype the FEA, or sell it for more than what it was supposed to do. And so, you know, trying to bring along the whole team saying, you know, 'here's a tool, here's what it can do, and can't do.'"
No. 11	No data on initial views/experiences with communication about FEA results. On this project, did not recall the FEA results seeming unclear, and stated that "It seemed like Jerrod did pretty good presenting his results to the team."

Participant	Accuracy
No. 1	Previously, had not seen FEA results presented that did not seem trustworthy or accurate. By the end of this project, acknowledged that FEA results are not perfectly accurate, but also noted that defining the necessary accuracy is itself a judgment call. Remarked, "You know, accurate is… it's almost like, alright, define accurate? What is your… if you're within 10 percent, or 2 percent, or whatever? I think they were fairly accurate, even though there were some points in the model versus the actual data that were off, but I think overall, it did truly reflect what we saw when we went and ran the tests." Also remarked, "There were, in some cases, some differences between what was predicted and what we measured, but I don't think it was outside of anything that certainly I would have expected in comparing the results."
No. 2	No data on initial views or past experiences with the accuracy of FEA results, although in the interview at the end of the project, remarked, "If you don't have a good start - if you don't have a good model to start with - you can go chasing down the wrong way, from what I've seen on other projects." By the end of this project, did not express strong views one way or the other regarding the accuracy of the FEA results. Simply summarized their observation that some results matched better than others, and that the test results were used to fine-tune the models.
No. 4	Previously, had not seen FEA results presented that did not seem trustworthy or accurate. At the conclusion of this project, when asked, did not recount any issues with the accuracy or clarity of the FEA results.
No. 5	Previously, had not seen FEA results presented that did not seem trustworthy or accurate. On this project, seemed impressed with the agreement between FEA and test results. Stated, "You know, we went back through the results and looked at the analysis versus the actual confirmed results, and it was really interesting. A lot of the analysis matched right on with the actual testing that we did. So the results in hardware were the same as they were in software in a lot of cases." Also acknowledged, "There were a few that were inaccurate, but they were at certain high frequencies… so it was one of those things that - okay, at this point, the model maybe broke down a tiny bit. Let's go back and look at what it did and iterate - you know, just as you would expect for any model. You know, there are certain areas you would need to focus on at different frequencies." Summarized by stating, "It made me look at analysis as saying… there are less flaws in it than I would typically think an analysis would have."
No. 6	No data on initial views or past experiences with the accuracy of FEA results. On this project, observed that "There is some inaccuracy that Jerrod presented in his results, as far as an electrical engineer is concerned,

Participant	Accuracy
	it looks pretty well correlated with the test results."
No. 7	In the past, has seen FEA results that did not seem trustworthy and/or accurate. On this project, stated, "I was actually pretty surprised at how accurate he - Jerrod - got it, in the kind of qualitative sense. But a lot of the peaks of all the frequencies were close to where they actually were, and matched up with the test data." Did acknowledge that "there were a couple channels on the accelerometers which seemed a little off." Made an interesting observation: "It seemed like the important ones sort of matched up to the test data, which ended up, I think, being pretty good. So, it's like, I don't know whether it was just chance that the important ones matched up, or if there was something about things we thought unimportant that made it so it was harder for the FEA to simulate, or what." Evidence of good, critical, reflective thinking about how assumptions in the FEA model affect its accuracy.
No. 8	No data on initial views or past experiences with the accuracy of FEA results. On this project, stated results were clear but could not speak to accuracy.
No. 9	In the past, has seen FEA results that did not seem trustworthy and/or accurate. At the conclusion of this project, did not really make strong statements one way or the other regarding the accuracy of the FEA results. Rather, referred to the iterative process of using test data to refine the FEA model. "I think as Jerrod continued to work with both testing and data, and the model, then he was able to get better understanding of how to model things… Along each step of the way, [he] was able to say, 'Okay, I built the model, these are the assumptions I made, this is what it's looking like, this is where it's matching well and where it's not matching well, and these are some of the things that may contribute to that.'" Recommended that I speak with experts from the FEA modeling community for advice on optimal ways to figure out which improvements to the model are actually necessary / responsible for observed disparities between FEA results and test data.
No. 11	No data on initial views or past experiences with the accuracy of FEA results. At the conclusion of this project, when asked, did not recount any issues with the accuracy or clarity of the FEA results.

Participant	Time required
No. 1	Previously, had seen FEA used early on in the design process, and in fact stated, "FEA should lead and keep pace with design activities." Regarding this project, never really remarked about the time required to utilize FEA in the product development effort.
No. 2	Previously, had seen the time required to utilize FEA be a factor in deciding whether or not to use it, and noted

Participant	Time required
	that from past encounters with FEA, its use tends to lag the design process. However, noted that having a reliable design model with which to start should help prevent time from being a major factor. Regarding this project, never really remarked about the time required to utilize FEA in the product development effort.
No. 4	Previously, had NOT seen FEA used early on in the design process, stating, "I would imagine it would be difficult for FEA to keep pace with design activities," and that FEA "could be costly in terms of time." At the end of this project, noted, "I think it's worth the time, but it's hard to get that time when you're on a fast-paced project." Also observed that "trying to figure out which features are necessary and which features aren't seemed like a challenge… and that seems like the biggest challenge with FEA keeping up with the design process, is just trying to fine-tune the model as you go along."
No. 5	Reflecting back to the beginning of the project, commented that "I was a little intimidated by how long it would take to make that model," and "I think people tend to shy away from FEA just because there's an initial investment -- a time investment." After the presentation that included the test results compared directly to the test data, this person asked me how long it took to build and run these models, to which I answered about .1 - .25 FTE over 6 months; to run one high-priority model (i.e., working full-time on it), and import test data for comparison, would require about 1 month. In the interview, at the conclusion of the project, stated, "You know, it took him some time to develop the model, but I think overall, … it was something that he was able to perform on his own in a reasonable amount of time," and that "I think he did it extremely well, and basically undersold his ability to really do it in a timely fashion."
No. 6	Initially, had NOT seen FEA used early on in the design process, but recognized that FEA "should be more useful when kept in pace with design activities, allowing designers to see an immediate feedback." Later, while reflecting back on the beginning of the project, stated that "knowing how long it usually takes for FEA results to come out, and how fast we're going on this project, I didn't think it was really that feasible." This seemed to be based largely on one previous encounter with FEA, where the "FEA results just came in way too late. The design was done, it was already in production, and now I saw this thermal analysis of my… design… it almost doesn't matter anymore. It's almost like, money wasted… especially in that case, it was that it came in, and they didn't see any problem. And you're like, okay, well I already know that, because I had already proven it in the actual qual [testing]." On this project, commented that the design and FEA results were presented "sort of right before our testing started, and I think it could

Participant	Time required
	have been done even earlier," although noted that "… Jerrod did as much as he could to keep up with this project," and that "we're actually looking at it during this whole development process." Even so, issued a general caution that the person doing the FEA "… would really have to keep up with the rest of the project -- meaning that when he's doing his analysis, he really has to present his progress -- like what he's been doing… if they want their results to be considered in the program." When asked about their view of the legitimacy of FEA as an engineering approach, connected it to the idea of the amount of time required to utilize FEA.
No. 7	Initially, had NOT seen FEA used early on in the design process. Regarding the relationship between the two, stated that "my current experience seems to suggest [FEA] lags, or it is being used as a way to validate what was seen in the testing, with no other application." Reflecting back to the beginning of the project, commented that they do not "…have a lot of experience, and I wasn't sure, without spending months on it, how good of results we could get. But just looking at it now, I'm happy with the results we got from this initial FEA study."
No. 8	Reflecting back to the beginning of the project, remarked, "I was slightly skeptical because I had never seen the FEA analysis done on something that didn't exist… I was more concerned about the timeline than the ability to do it. In my experience, it took a long time to build the model -- to get all the programming and the numbers correct, all the math correct so as to have a capable model." Interestingly, "it's been done -- it is feasible." Interestingly, on this project, observed the 'time' issue as being an overall benefit of FEA, rather than a hindrance: "Where I found Jerrod's use of FEA to be beneficial was it gave him confidence early… and because of that we were able to put forth a very aggressive schedule, that so far we've been able to follow. And so that's where I see the benefit of it, is pushing things forward, faster, in order to meet some pretty strict deadlines."
No. 9	Initially, had seen FEA used early on in the design process. Noted that FEA results are most valuable or useful when they can be obtained quickly, and noted that whether FEA is able to keep up with design activities "depends on the fidelity requested. If the engineer does the FEA, it keeps pace, and usually it is pretty simple." At the conclusion of this project, stated that "In our business world, I think Jerrod's hitting on it -- trying to develop those tools that can be used up front for the conceptual tradeoffs - so very quick. It doesn't have to have an absolute answer, but provide guidance: 'This looks like it's going to be worse than that,' you know, 'this is much better.' So having a lot of belief in the model, even if the model is just giving

Participant	Time required
	direction." Also stated that this project supported their view on the need for quick results from FEA models, stating that "if we didn't get information back within, you know, 'weeks' timeframe, then it wouldn't have been useful, because the team was moving ahead."
No. 11	No data that can be specifically isolated to an initial view, but did make several comments during the interview about needing sufficient time in the schedule to allow for the use of FEA. Later, regarding some other FEA analyses that I performed for a different project, inquired about how long it took for me to build and run the models, stating, "Just curious how quickly you can turn these around."

Participant	Dollar cost
No. 1	Initially, noted that "the disadvantage to incorporating FEA is, like most advanced analysis, the hit to one's budget." Later elaborated on this, describing the way that FEA has traditionally been used at Sandia, in which we "tend to have a group of people off in another department or division, and their sole job is to do this type of work. So if you're off funding somebody else, it's generally going to cost you a lot more money than if that capability is located within the project and design team." Also noted that "I have been in situations where the decision has been made not to do that type of analysis because the project simply cannot afford the extra labor and the extra overhead from having an outside group of people do the work for you." Noted that the dollar cost of using FEA on this project was only "a minor factor" because the analysis is being done by a member of the design team whose time is already covered by the project budget, and is being done using a desktop computer, so we are not paying for time on the supercomputer clusters.
No. 2	Previously, had not seen the cost of FEA be a factor in deciding whether or not to use it. On this project, did not have any view into the cost involved with using FEA.
No. 4	No data on any initial views of the dollar cost of using FEA. On this project, did not have any view into the cost involved with using FEA.
No. 5	Previously, had seen the use of FEA impact funding allocation within a project. On this project, described the dollar cost of using FEA as much lower than taking an iterative approach to design using hardware testing. "Jerrod did things really quickly. And so to me, it was a cost-versus-time benefit, and in our case we just didn't have enough time to build something up, go through that iterative process, and then build it up again, and then… we just didn't have the time or the budget. And so really Jerrod's analysis was really way cheaper than it would have been to do some sort of

Participant	Dollar cost
	iterative process and way quicker. And so in terms of him being able to deliver results that we needed in a timely fashion, it was really important. To me, it was a huge benefit, and it was performed inexpensively."
No. 6	No data on any initial views of the cost of using FEA. On this project, did not have any view into the cost involved with using FEA. Did issue a general caution that engineers using FEA need to watch out for situations where a project is running out of money, and project management might cancel all analysis efforts and instead fund only hardware testing.
No. 7	No data on any initial views of the cost of using FEA. On this project, stated, "I'm not sure of the overall cost, but I think it's minimal at this point." Also noted that one planned use of FEA to evaluate a minor design change would not only have a small cost, but would actually save money vs. repeating the vibration and shock testing.
No. 8	No data on any initial views of the cost of using FEA. On this project, commented that FEA actually had a beneficial impact on cost, in that "if the analysis prevents us from having a failure in testing, followed by a redesign and rebuild, then it will save us about $300k."
No. 9	Previously, had seen the use of FEA impact funding allocation within a project. Regarding the cost of using FEA on this project, stated, "I don't think it was a factor in this particular project."
No. 11	No data that can be specifically isolated to an initial view, but did make several comments during the interview that seemed to be general comments about the dollar cost of utilizing FEA; e.g., "It's my perception… that developing the models takes quite a bit of time, and the labor cost associated with that." On this project, was not sure of the dollar cost. Later, in a meeting, described their impression that using FEA early in the design process is "an investment in the modeling activities that probably only pays off in production, if at all… so is it worth it?"

Participant	Desire to understand FEA
No. 1	Reflecting back to the beginning of the project, placed a relatively high value on personally understanding FEA (giving it a rating of '6' or '7' on a scale of 1 to 10). Noted that this was because previously, they did not feel they were "in much of a position on some… other projects to really make use of it, so the question never really came up." At the end of this project, expressed a greater value placed on personally understanding FEA.
No. 2	Reflecting back to the beginning of the project, placed a relatively low value on personally understanding FEA (giving it a rating of '2' or '3' on a scale of 1 to

Participant	Desire to understand FEA
	10), remarking, "I understand what it is. Do I need to know the details? No." At the end of this project, placed the same value on personally understanding FEA. Commented, "You rely on the other experts, so it's not real important to me. I think it's a great tool. It's definitely useful, and it will help us go along. But, my understanding of it? No, I don't think I need to know. I mean, you got to rely on the right people."
No. 4	Reflecting back to the beginning of the project, placed a "very low" value on personally understanding FEA (giving it a rating of '2' or '3' on a scale of 1 to 10). Noted that, as an electrical engineer, "we don't directly see the impact, other than the levels that the board might see. It doesn't drive our design decisions too much on the electrical side." At the end of this project, expressed a greater value placed on personally understanding FEA (giving it a '5').
No. 5	Reflecting back to the beginning of the project, placed a low to moderate value on personally understanding FEA (giving it a rating of '4' on a scale of 1 to 10). Commented that, "with my background as an electrical, it wasn't that important." At the end of this project, expressed a "much greater" value placed on personally understanding FEA.
No. 6	Reflecting back to the beginning of the project, placed an extremely low value on personally understanding FEA (giving it a rating of '1' or '2' on a scale of 1 to 10). At the end of this project, expressed a greater value placed on personally understanding FEA (giving it a '5'). Commented that "I can see the usefulness, and I can see how it could affect… not my design, but the boundaries on my design, really, if you're just talking about the physical characteristics of my design… It wouldn't affect me that much, not as much as it would affect a mechanical engineer."
No. 7	Reflecting back to the beginning of the project, placed a moderate to relatively high value on personally understanding FEA (giving it a rating of '7' on a scale of 1 to 10). At the end of this project, expressed a greater value placed on personally understanding FEA. Commented that, "If we're going to be using it more, I should have a better understanding of it, just so I can… catch any of the assumptions, for example, that are bad, or help out, or… anything you can put in to make it better, is going to make the results better. So I think if I have a better understanding of it, I think it's more important for me now since we're going to be using it." When presented with the opportunity, was excited to perform modal analysis on the design of an important bracket, despite little previous exposure to this type of FEA.
No. 8	Reflecting back to the beginning of the project, placed a moderate value on personally understanding FEA (giving it a rating of '4' on a scale of 1 to 10), and commented

Participant	Desire to understand FEA
	that, "I like understanding what's going on, but it wasn't necessary in my role on the project, to really dig into the mechanics of the FEA." At the end of this project, expressed no change in their value placed on personally understanding FEA, because "I still don't have a need to really dig into the details, but I'm glad someone on the team does know more about it than I do."
No. 9	Reflecting back to the beginning of the project, placed a moderate to relatively high value on personally understanding FEA (giving it a rating of '7' on a scale of 1 to 10). At the end of this project, expressed an even greater value placed on personally understanding FEA (giving it a '9'). Explained that "Now I want to be in a role to promote more dialogue about integrating FEA in our products. So not necessarily to promote, 'You must use it,' but to really have these conversations about, 'When is it useful? How can we use it? What's it's benefit? What should we expect of our staff?' So for that reason, now I want to know more and more about it, so I can be more informed."
No. 11	Reflecting back to the beginning of the project, placed a low value on personally understanding FEA (giving it a rating of '2' or '3' on a scale of 1 to 10). At the end of this project, expressed a greater value placed on personally understanding FEA, noting that "since I did see that FEA could be used, if I had a project now and wanted to use it, I will need to understand it better and how it could help."

Participant	Learning process
No. 1	No data on any initial view of FEA as a learning process. For this project, commented that the use of FEA "will be used as a stepping stone to help us go back and particularly if we have issues in the second project, to look and see how those components responded in a slightly different mechanical configuration with this first project. So I tend to look at things, just how does it… what's the feed-forward of information from the old project to the new one." This seems to hint at a view of some kind of a learning process, although it's not clear whether this view is regarding the two product designs in general, or in particular the use of FEA to develop those products.
No. 2	No data on any initial view of FEA as a learning process. For this project, remarked that, "For someone with better knowledge and experience [with FEA], then as you get results, you can refine the models, which leads to even better results and thus greater legitimacy." Continued on, saying that important factors are the person's level of experience with FEA, and the extent to which they "follow up" and compare the FEA results to experimental measurements. Seems to suggest a learning

Participant	Learning process
	process that occurs as a result of this iterative process.
No. 4	No data on any initial view of FEA as a learning process, nor over the course of this project.
No. 5	No data on any initial view of FEA as a learning process. For this project, remarked that, "I think there were some things learned, too, and I think that's great with FEA - in terms of being able to say, 'yeah, we think this is what's going to happen, this is what actually happened.' So it's iterative in terms of Jerrod, too - he's learning, and I think that as you get further down the road, you're really going to understand exactly how the hardware is working. And for Jerrod, it's going to work long term, because he's going to use these results, you know, throughout his career, probably, to re-iterate the process." Seems to suggest a view that the use of FEA is an iterative learning process for both the team as a whole, and for the analyst in particular.
No. 6	No data on any initial view of FEA as a learning process. For this project, after commenting on the importance of establishing confidence and team buy-in in the FEA models and effort, remarked that, "What's important is to be able to keep up, build confidence, and have time - or a chance - to go back and review and revise your models, to improve your skills in building FEA models." So there is clearly a view here that the FEA analyst is learning as they use FEA.
No. 7	On the FEA survey, noted that in the past, FEA was sometimes used just for the sake of doing it. "For a class design project it was a requirement with little verification of the model. It was done more an exercise in doing it, but it added no value to the overall project. I was also tasked with doing some FEA at work. It turned out just to be busy work and the parts I was doing analysis on were already in production." Regarding the use of FEA on this project, followed up on this initial view: "Originally, I thought this was kind of a lot of work to put into it, because we were getting kind of one thing out of it at the beginning. But I think of it more as a kind of proof-of-concept for this project now. I think we could definitely make more use of it in the future, and I think this kind of just shows that it can work for small things like this. So maybe, for this project, if taken kind of in an isolated sense, and we don't follow through with this - it's kind of like, well, we just kind of did it just to do it. But if we do use what we learned from here on the second project - Project 2 - I think that will be very valuable." Suggests a view of a learning process that occurs as FEA is used iteratively, and moreover, that the real value from FEA comes as a result of this iterative learning process. This view seems to have arisen at least in part due to this project.

Participant	Learning process
No. 8	No data on any initial view of FEA as a learning process, nor over the course of this project.
No. 9	No data on any initial view of FEA as a learning process. For this project, commented specifically on how the use of FEA on the first project would in turn help the second project. "… the FEA, in this particular case, I don't think brought to light things that they didn't know, but it confirmed those decisions and assumptions about what they were doing. So then it provides more credibility to their design decisions and the direction they went. And, we all were aware that this was a 'stepping stone,' and the FEA was gearing up to help support project number 2, as well." Suggests a view of FEA as a learning process.
No. 11	No data on any initial view of FEA as a learning process, nor over the course of this project.

Participant	Opinions on appropriate use
No. 1	Near the beginning of the project, described the use of FEA on a previous project in which the FEA modeling activities and the experimental testing were very tightly coupled, with progress on one informing the next step on the other. Seemed to hold this manner of using FEA in high regard. By the conclusion of this project, articulated several views on how FEA in particular (and modeling and simulation in general) should be used: (1) "I would say that the one thing that it has - if it's changed anything - it's that it has really reinforced that fact to me that you need to have that capability within your design team or in your project team"; (2) "I think that is something… FEA… that's a question that when you start a project, should always be asked, and then you look at the scope of the project, really what are you doing, and then make the decision from there. But I think it should be a question that should always be asked when you're setting up a project"; (3) "I'm a proponent of [FEA]. I'm a proponent of, well, any modeling and simulation, and, you know, with the caveats of you must have a rudimentary understanding of your system and what you're trying to model and simulate, so that you can then make a hopefully informed decision on the results that you get back from your modeling." Not clear whether these views existed from the beginning, or arose as a result of experiences on this project.
No. 2	No data on any initial opinions on appropriate ways to use FEA. By the conclusion of this project, made a couple comments suggesting the formation of some opinions. "One of the good things that he did was he did the testing, he took the model and then he compared it to the actual results." And, "A lot of the times that I saw it in the past, it was kind of like, we saw a problem, let's try to use this to help fix it, whereas

Participant	Opinions on appropriate use
	this time, I think Jerrod's trying to - he was using it early on, and trying to help, and I think that's a good thing to do."
No. 4	No data on either initial opinions, or opinions formed over the course of this project, on appropriate ways to use FEA.
No. 5	No data on any initial opinions on appropriate ways to use FEA. By the conclusion of this project, remarked, "Hopefully in the future… you know, obviously we're always time constrained, but Jerrod's analysis was really quick, it was really fast, so I think in the long term, we're going to get better at it, and hopefully be able to integrate that early in the project, really quickly, all the time." Feels we could have done an even better job achieving this on this project had the time for model development been better understood.
No. 6	Reflected back on previous experiences with FEA and described how the analysis results took way too long to be completed, and essentially had no impact on the product development. At the conclusion of this project, emphasized that "what's important is to be able to keep up, build confidence, and have time - or a chance - to go back and review and revise your models, to improve your skills in building FEA models." Also remarked that more periodic updates - even informal ones - throughout the course of the FEA effort would be appreciated.
No. 7	Near the beginning of the project, expressed views that some amount of hardware testing should be performed to support a FEA model, and that FEA model details (rather than only the results) should be disclosed and retrievable. At the conclusion of this project, reiterated those views, and made remarks expressing support for the way FEA was utilized on this project, but did not make any remarks suggesting the formation of new opinions as a result of this project.
No. 8	No data on any initial opinions on appropriate ways to use FEA. Regarding this project, repeatedly emphasized that much of the benefit of using FEA came from the fact that it was used early in the design process, which permitted a more aggressive product development schedule. Never phrased these remarks as 'opinions' that it should always be used this way, but rather as observations that it was beneficial on this project.
No. 9	Initially, described a litany of ways in which the use of FEA can be helpful to a project or hindered by poor implementation, implying some strong initial opinions based on past experiences with FEA. Examples of the things to do included strong teaming between design engineer and analyst, obtaining results quickly, using FEA in conjunction with physical testing, and using good judgment to determine when and how to incorporate FEA. Examples of the things NOT to do included assuming the FEA could tell you more than it actually can, not planning for model validation testing, not ensuring

Participant	Opinions on appropriate use
	strong communication between design engineer and analysis, and allowing factors other than project/product needs dictate how FEA was implemented. By the conclusion of this project, reiterated similar points, with a particular emphasis on (1) using FEA to obtain answers quickly, and (2) using FEA to obtain relative answers, in order to provide directional guidance about design decisions. Also noted that previously, would have envisioned only using FEA to answer very specific, smaller-scale questions, rather than modeling the entire product, as was done in this project.
No. 11	No data on any initial opinions on appropriate ways to use FEA. By the conclusion of the project, made several observations about the use of FEA on this project, but nothing that really directly amounted to an 'opinion' that it should be used or implemented in a particular way.

Participant	Conceiving of new applications
No. 1	This person did not suggest any potential uses of FEA pertaining to this first case study design project. Overall, this may suggest a baseline in which FEA has a limited role in this person's thinking, at least as evidenced by re-invention. (However, over the course of this project, did suggest several uses of FEA pertaining to the second case study project, which in its early stages was occurring in parallel with the first project. Those instances will be discussed in the second case study analysis.)
No. 2	This person did not suggest any potential uses of FEA pertaining to this first case study design project. Overall, this may suggest a baseline in which FEA has a limited role in this person's thinking, at least as evidenced by re-invention. (However, this person did suggest at least one use of FEA pertaining to the second case study project, which in its early stages was occurring in parallel with the first project. That instance will be discussed in the second case study analysis.)
No. 4	At the conclusion of the project, described how FEA could be used to "probe around different locations in the system and effectively 'instrument' the system in places that we couldn't instrument in actual hardware." We never actually used the FEA for this purpose (although we could), so it's not clear if this person was under the impression that we did use the FEA model in this manner. Judging strictly by what was said in the course of the interview, it seems more likely they were simply suggesting that we could have, in which case this is a great example of re-invention. This person also drew on an idea presented in a class and asked if FEA is

Participant	Conceiving of new applications
	a good tool for selecting appropriate points for locating accelerometers (to avoid nodes). Again, this is a great example of re-invention: taking what has been learned about FEA and recognizing that FEA could be a good tool to address a problem presented in another context.
No. 5	This person asked whether or not this type of simplified FEA modeling could be used to address failure and survivability issues of the very same electronic sub-component that we are installing into this design as part of this case study design project. This person felt that other users and customers of that component would be interested in some sort of a study of its overall robustness in vibration and shock. We discussed the technical merits of such an approach at length. Regardless, this was an interesting example of applying what was learned about this type of FEA to other technical challenges faced by this individual.
No. 6	This person did not suggest any potential uses of FEA pertaining to this first case study design project. Overall, this may suggest a baseline in which FEA has a limited role in this person's thinking, at least as evidenced by re-invention.
No. 7	On more than one occasion, suggested the use of FEA to address technical issues. In the first instance, shortly after the vibration testing of this prototype occurred, there was a need to modify two relatively heavy parts that sit immediately adjacent to our component, and a concern existed as to whether changing the design of those parts could couple in and alter the vibration and shock levels experienced by our component. This individual remembered that I had constructed a version of the FEA model that included those parts, and suggested we use it to explore the effects of the proposed design change. Later, during a second round of vibration testing, proposed that we use it as an opportunity to collect vibration/shock data for more fully validating this alternate version of the FEA model. During the interview at the end of the project, when asked, "In the FEA survey, you mentioned that FEA can be used to understand problems seen in testing. Did you see anything on this project that supported your view, or made you see things differently?" responded, "I actually didn’t think about this until I read the interview questions, but… There was one issue we were having during testing, and just by being asked that question, I just thought of a new use for FEA which might be able to answer some questions about the cause of that problem." Also remarked during the interview, "I’m starting to think of more ways something like this could be integrated into answering quick questions on the design - not necessarily before or instead of testing, but in addition to testing." Clearly, this individual made significant strides in terms of thinking

Participant	Conceiving of new applications
	critically about how FEA might be used to address questions that they face.
No. 8	This person did not suggest any potential uses of FEA pertaining to this first case study design project. Overall, this may suggest a baseline in which FEA has a limited role in this person's thinking, at least as evidenced by re-invention.
No. 9	This person did not suggest any potential uses of FEA pertaining to this first case study design project. Overall, this may suggest a baseline in which FEA has a limited role in this person's thinking, at least as evidenced by re-invention.
No. 11	This person did not suggest any potential uses of FEA pertaining to this first case study design project. Overall, this may suggest a baseline in which FEA has a limited role in this person's thinking, at least as evidenced by re-invention.

Participant	Likely to carry FEA forward
No. 1	During the interview, reflected back on past projects and stated that they were not "…in much of a position on some of my other projects to really make use of [FEA], so the question never really came up." Looking forward, remarked that "I think regardless of what we may or may not have learned on the first project, we're going to move forward with [the use of FEA] on the second project." This, coupled with this person's overall enthusiastic level of support for the use of FEA, suggests they are very likely to carry its use forward to future projects.
No. 2	The idea of using FEA as a design tool (rather than to troubleshoot problems found in testing) seemed new to this individual. By the conclusion of the project, stated that "…if somebody came and asked, I would recommend that this is another tool that they could use for designing up front." Based on this, could be construed as either inconclusive, or as at least somewhat likely to carry the use of FEA forward to future projects.
No. 4	Several statements paint an overall picture of this person's view. On the one hand, by the end of the project, stated that "I can see the value in FEA. It does help make design decisions, before fabricating the actual parts." And, expressed interest in knowing the vibration and shock levels that the circuit boards would see. But noted that this information would probably only affect the electrical design if there were sensitive components, and remarked that "I think [FEA] is worth the time, but it's hard to get that time when you're on a fast-paced project." Overall, the data seems inconclusive as to whether or not this individual will carry the use of FEA forward to future projects.

Participant	Likely to carry FEA forward
No. 5	Initially, viewed it as, "…analysis is great, but it's on the side." By the conclusion of the project, stated that we should always make an effort to match test results via analysis. Commented that "You can't quantitatively say, 'I can't use this,' or, 'I don't want to use it,' or, 'we don't have the budget.' We have to make the budget for this." Noted that in the future, "I think I'll approach it as saying, we need budget for analysis for every project I do. So, it made a big impact." Overall, this person seems highly likely to carry the use of FEA forward to future projects.
No. 6	At the conclusion of the project, commented that "In my future designs, I would certainly put it under my consideration - let's just put it that way - because of the confidence that Jerrod has built for the first project." But also notes, "I think it's more beneficial to mechanical engineers, in a way, because they have to choose the design." As an electrical engineer, "it gives me more confidence that if Jerrod wants to add a screw and take away my board space, it's perfectly fine with me." So at the very least, this person seems likely to carry forward an openness to the use of FEA in the product development process and the influence it can have on shaping (physically) the design of their circuit boards.
No. 7	In the interview at the conclusion of the project, reflected back and commented that "Originally, I thought this was kind of a lot of work to put into it, because we were getting kind of one thing out of it at the beginning. But I think of it more as a kind of proof-of-concept for this project now. I think we could definitely make more use of it in the future, and I think this kind of just shows that it can work for small things like this. So maybe, for this project, if taken kind of in an isolated sense, and we don't follow through with this - it's kind of like, well, we just kind of did it just to do it. But if we do use what we learned from here on the second project - Project 2 - I think that will be very valuable." This seems to imply a strong likelihood of carrying the use of FEA forward to future projects.
No. 8	By the conclusion of the project, remarked that "In terms of setting up a project, I would say if we have the resources to do FEA analysis, I would definitely recommend it for a similar project in the future, such as project number 2." Continued on, saying that as a result of this project, FEA is now more a part of their design thinking process "because I know now to put it in the design process, even though I'm not the one doing it. … I would recommend it moving forward to other programs in a similar situation." Clearly, seems likely to carry the use of FEA forward in terms of their thinking and project planning.
No. 9	At the conclusion of the project, summarized their view

Participant	Likely to carry FEA forward
	of how to carry the use of FEA forward as follows: "Now I want to be in a role to promote more dialogue about integrating FEA in our products. So not necessarily to promote, 'You must use it,' but to really have these conversations about, 'When is it useful?' 'How can we use it?' 'What's it's benefit?' 'What should we expect of our staff?'" Separately, on numerous occasions (at least 5 over the course of the first case study project), this person has referred other engineers, especially newer staff, to me for help getting started with various types of FEA analyses. Taken together, these clearly suggest this person is very likely to carry the use of FEA forward.
No. 11	The overall theme present in many of this person's comments was "budget and schedule" -- i.e., FEA is promising and can be worthwhile but requires time and money. Near the end of the project, this person showed signs that they are perhaps still in the process of forming their opinion on whether or not the use of FEA for our products is a good value proposition. In one instance, in a meeting with various managers, remarked that their impression was that utilizing FEA represents an investment in the modeling activities that probably only pays off when the design enters production, and therefore questioned whether or not it was worth it. On another occasion, after seeing the FEA results on the modified ballast design, asked me how long it took, stating "just curious how quickly you can turn these analyses around." So it is inconclusive whether or not this individual is likely to carry the use of FEA forward to future projects.

Appendix H: Case Study 2 Framework Matrix Summaries

The following tables are taken from the NVivo Framework Matrix for the second case study and present summaries of the coded case study data (survey, interview, and field notes).

Participant	Product design impacts
No. 1	No real discussion of product design impacts at any point during the project. This participant was less involved in the actual design work which could be a reason.
No. 4	After seeing the comparison of the test results to the original FEA predictions, this participant approached the investigator with some thoughts on how to make the design better. Would asymmetric mounting points, or staggered mounting points going up the stack, help prevent the resonances where all boards participate? Would rings to capture the board edges help? It is clear this participant like thinking about the mechanical design aspects of the project, even though this participant is an electrical engineer. In that sense, maybe FEA can provide a medium for design thinking by more of the team. At the conclusion of the project, when asked about how to help the FEA results have a real impact on the design process, suggested starting the FEA modeling early on, so that the FEA results can be leveraged for the actual design.
No. 7	At the beginning of the project, when asked how FEA was most likely to be beneficial on this project, described several steps about how to use or implement FEA, followed by things it could be used for: vibe and shock, minimizing the thicknesses of housings or supports (to deal with weight restrictions). The latter of those is a specific product design impact. So this participant was looking to see FEA used in this way. At the end of the project, when asked how beneficial FEA was for the project, stated, "So far, I think we have a good base, but we haven't actually done anything with it, other than to show that, oh, hey, our model matches our test results… But hopefully in the future that number would go up as we have design changes that can be evaluated using the model that we have. It hasn't come up yet in this project, so its usefulness hasn't really shown itself… I think the 'use the model to help with design decisions' is coming, because I think there will be changes we'll have to make, that will kind of see how beneficial it is." Mentioned a belief that the time required to run the models may have been a factor in not using the FEA models for small issues and design decisions.
No. 8	No real discussion of product design impacts at any point during the project. This participant was less involved in the actual design work which could be a reason.
No. 11	At the beginning of the project, indicated that they

Participant	Product design impacts
	would be looking to the FEA to identify weaknesses in the design. At the end of the project, when asked about how beneficial FEA was for this project, remarked, "I think it helped the team learn about FEA, and introduce the group as a whole to FEA and how the results can match the model, and therefore the model can help you. But, I'm still not 100 percent sure it actually drove any design decisions, so, in that sense, I'm not sure it helped the design aspect. … I'm not sure it actually drove any true, major design decisions. So, um, I don't know if that's a good thing or a bad thing. But, I don't know that it helped, because there were no design decisions that they were basing off of it." So this participant is clearly looking for evidence of more direct product design impacts.
No. 12	At the beginning of the project, indicated that in the past, has seen FEA impact product design, and remarked that FEA can be beneficial for "predicting what may occur during testing, and/or predicting failure locations." At the end of the project, when asked if FEA was helpful for spotting potential flaws in the design, remarked, "I think so, because I think the FEA analysis that were ran can show where things can be improved if needed. I think that if you needed to make design changes, um, you know where to start, and how… You know where you can make changes with knowing where strengths and weaknesses are already in the design." Further commented on that thought, stating, "I think it's going to be a useful tool in the future if we ever have to make design changes or anything like that." So, seems to be answering that the FEA has the potential to impact design changes that may be needed in the future, but so far, direct product design impacts were limited.
No. 13	No real discussion of product design impacts at any point during the project.

Participant	Integration with design process
No. 1	At the beginning of this project, commented that an important thing learned from the first project (case study 1) was "… the whole idea of working on the FEA itself, developing the models, developing a process for doing it, starting to understand how much time and effort is need to develop the models… as we get it folded into the design and our testing and qualification activities." So there is some focus on the importance of learning how to integrate FEA into the overall process. At the end of the project, when asked if FEA was integrated with the design process, remarked, "Yes, most definitely. And in fact, that was a goal of mine. I am the project lead, and so it was a goal of mine to integrate FEA as much as possible. And it's also kind of an overall goal of Sandia's, is to try and get more

Participant	Integration with design process
	modeling - both electrical and mechanical, but here we're focusing on just the mechanical - into our design projects." Also commented that in the future, they would generally be an advocate for FEA, "… as long as you start out a project with the idea of using FEA so that you can put that into your schedule and understand that it takes time to get the initial models set up and working and it just gets folded right into the design process." So their general support of using FEA hinges on making sure it is properly integrated with the design process.
No. 4	At the beginning of the project, remarked extensively on different ways that FEA can be helpful in design process, such as understanding vibration and shock levels at different locations on the circuit boards to help guide the placement of sensitive components, and guiding design decisions prior to actually fabricating parts. Also commented, "… that seems like the biggest challenge with FEA keeping up with the design process, is just trying to fine-tune the model as you go along." At the conclusion of the project, did not elaborate much on design process integration, but simply remarked, "Integrated? Yeah, uh, mostly by Jerrod, but yeah, it seemed like he included that in his process."
No. 7	During this project, this participant was working on the design of the fixture for vibration and shock testing the prototype. The research investigator suggested using FEA modal analysis to make the fixture light but also as stiff as possible. The participant was excited for this opportunity to practice using FEA modal analysis. At the end of the project, when asked if FEA was integrated with the design process for this project, commented that "So far, I think we have a good start. We have - or Jerrod has, rather - created the FEA model. And we've kind of verified it through testing, and it tends to match really well, save a couple issues which I think he knows he has. So it matches really well there. So it's kind of to be said whether or not it's worth it - well, I think it's still worth it so far, because we don't know what's coming up - but we'll see whether we get use of it, depending on what things come up, and what design decisions we have to make in the future." So seems to believe we've done everything right so far, but the culmination of that effort of developing a model that we now have confidence in, is using it to guide design decisions and design changes in the future.
No. 8	At the beginning of the project, remarked that FEA was becoming more a part of their design thinking process "because I know now to put [i.e., plan for] it into the design process, even though I'm not the one doing it." At the conclusion of this project, when asked what factors would be important in terms of helping the FEA results to have a real impact in the design process, commented that "I think the biggest factor for me would

Participant	Integration with design process
	be how well they integrate into the design team and our testing team. Either if it's one person - Jerrod - or if we have someone full-time modeling, I would like them to be intimately involved in kind of how our team structure is set up. And so, the main part would be to break down communication barriers that could exist between FEA modeling, design, and testing of the design and models, which there are no barriers now, because Jerrod does all three. But if we did separate these functions, making sure that they are one team and they can all get the right information at the right time would be my biggest concern." So integration of the person doing the FEA into the design team and design process is important in this person's view.
No. 11	Stated that FEA was integrated with the design process, but then seemed to caveat that statement somewhat heavily when describing factors that prevented FEA from being more beneficial. "It seemed to me that maybe the modeling was done in parallel with the design. So, I think to be really effective, you might do the model first, and then help you drive design decisions. But I don't think that was the case here - I think it was mostly in parallel. So, if we want it to be more impactful, it might have to be done sooner. And then, I don't ever see us being able to not test, so we're always going to have to do the testing anyway. But if there was time that we were confident enough in the models, or could prove that they were so good that we didn't need to test, then that would be extremely beneficial." So the limits to FEA's integration with design are (1) how quickly it can be done, (2) doing it soon enough and then using it to drive design decisions, and (3) reducing some amount of testing.
No. 12	At the beginning of the project, stated that they had previously seen FEA be integrated with design activities and used early in the design process, but remarked that "most of the design is completed based on quick analysis/calculation, and many times the FEA is done afterwards to see the overall result." At the conclusion of this project, remarked that when using FEA, "It has to be very well coordinated. Also, it's got to be done in parallel because a lot of times we can't wait for the design to be done and then create an FEA model, because it takes time away from the schedule. So it has to be completely integrated in order to make a real impact." Later, described what they observed on this project: "I think on this one, I really saw them go parallel, versus what I normally see, which is that the analysis is done after the design. I think on this one it was really work in parallel, and I think part of that was just because it was the same designer who was doing the analysis."
No. 13	At the conclusion of the project, indicated that they felt FEA was integrated with the design process, commenting that "all throughout, kind of the whole

Participant	Integration with design process
	design cycle, we were thinking about how we could get data to kind of 'point' back to the FEA analysis that was done, and kind of either verify, or kind of prove wrong that model." That comment is pointed at integration in terms of the complementary use of testing and analysis, and how they dovetail together. Also described, in general, the importance of integrating FEA into the design process in order to maximize impact: "[FEA] can work relatively seamlessly with the design, as long as you have someone who's well-integrated in the project and knows what's going on and can kind of keep up with the latest design decisions." This is speaking to integration in terms of communication and the person doing the FEA vs. the rest of the design team.

Participant	Design understanding
No. 1	At the beginning of the project, made the general statement that, "When you start looking at budget constraints, when you start looking at how requirements are being levied on us, then we need to change how we think about the design process, and start looking at these other tools that are out there, other than simply doing things the way we've always done them… [FEA is] just another tool that we need to think about making use of." Over the course of the project, this participant suggested multiple possible uses for FEA, including estimating the vibration and shock levels that various sub-components would see; using FEA to look at thermal issues; and placing certain components at different locations in the overall system, rather than inside the electronics assembly. When asked about what it is that makes FEA come to mind when they're thinking about a design problem, referred back to a project from years earlier, where FEA was used in conjunction with testing and engineering judgment, to expand capabilities beyond the limits of what could be tested experimentally, in order to assist the design and test effort and improve the design.
No. 4	At the beginning of the project, stated that being able to determine vibration and shock levels that the circuit boards would be subjected to in the new design would be useful information that FEA might be able to help with. After seeing the comparison of the test results to the original FEA predictions, this participant approached the investigator with some thoughts on how to make the design better. It is clear the presentation of the FEA results is causing this participant to reflect on their understanding of the design's behavior, and that this participant likes thinking about the mechanical design aspects of the project, even though this participant is an electrical engineer. When asked about this, and what it is that makes FEA come to mind when they are thinking

Participant	Design understanding
	about a design problem, remarked, "I guess, being able to - you know, using FEA is a way to find information that you couldn't get any other way. So in that sense, you know, like I mentioned before, not being able to instrument every location on a circuit, or spend the time to go shake every scenario - you know, you can rely on the FEA model. … So looking for ways to answer a question that you couldn't answer otherwise."
No. 7	No real comments that addressed the topic of design understanding at any point during the project.
No. 8	No real comments that addressed the topic of design understanding at any point during the project.
No. 11	At the beginning of the project, when asked if FEA could help with anything that is important to this person in their role, stated that it could be helpful for identifying weak links in the design. At the conclusion of the project, recalled one instance as follows: "You know, I can't recall the details, but I do think it did point out one possible issue. And, it may be related to those spikes that didn't meet test results. But I can't fully remember the details from the meeting. But I do think that it helped to illustrate areas of further investigation." Likely talking about the discrepancy at the edge of the third (smallest) enclosed circuit board. This is sort of an example of FEA being part of an overall path toward better understanding of the design's behavior.
No. 12	At the beginning of the project, commented that FEA is "good at predicting what may occur during testing, and/or predicting failure locations" and that "an early analysis can show/spot potential weaknesses." When asked about this at the end of the project, remarked that "Based on seeing the results of the test, and comparing it to the FEA model, I think because of the way they matched up, I think you could potentially use that for failure analyses later on. And it also gives you an idea of how things are responding from like a visual standpoint, versus looking at just the test data. You can see exactly where those are occurring in the system." This comment speaks to how modal analysis allows one to visualize how the parts deform and deflect during resonance, which is a good example of design understanding.
No. 13	At the conclusion of the project, described several examples of how FEA can be used to increase design understanding. Stated that, since this was a completely new mechanical design, "I think that having the FEA model was really useful, to be able to kind of nail down where areas of concern might be, so you can focus your engineering effort in those areas, as opposed to, you know, kind of guessing." Also commented that "Using it as a tool to support your engineering, and not necessarily depending on it as your only tool, but more just like one of the tools in your toolbox, and being

Participant	Design understanding
	able to focus your effort. I think that, in my opinion, that's probably one of the more valuable things that FEA can provide that few other tools can actually give you - you know, a very explicit definition of where you may have weaknesses in your design."

Participant	Confidence in design
No. 1	At the conclusion of the project, when asked to what extent the FEA influenced their confidence or engineering judgment about the design, remarked that, "It really - from my perspective - it really helps. … Though I'm an electrical engineer by training, I've worked on other projects that have made extensive use of FEA - in fact they could not have really completed the project without the use of it. So I've had a long history over the years with FEA. And, you know, I'm a big proponent of it, and a big fan of it. So, I think it allows you, it gives you more information, it also allows you to help to sometimes scope your experiments or testing if you've got some information from FEA. And of course then the two of them are hopefully synergistic, and building on one another."
No. 4	At the conclusion of the project, when asked to what extent the FEA influenced their confidence or engineering judgment about the design, remarked that "it did increase my confidence in the design," but that "I'm an electrical, so it didn't influence me a lot." No real elaboration provided.
No. 7	At the conclusion of the project, when asked to what extent the FEA influenced their confidence or engineering judgment about the design, remarked that "I gain some confidence knowing we have a better model now, and we could solve future issues with this model that we have. But I don't know if it gave me any extra confidence when we went into this round of testing, necessarily. But it will give me confidence for future changes and future testing." Later, elaborated a bit more on this point: "Going back to Project 1, I know we actually used some of the original model that Jerrod built for Project 1, and we changed some loads on it, basically, and we saw that the response was very similar, and used that as an argument for not having to re-test the design with the slightly different weight. So that's exactly what I would have wanted to see, and that's good - that…aided us in our engineering judgment…that such a change was indeed kind of on the trivial side, and wouldn't affect our component much. … On Project 2, I haven't seen it much yet. It's like, the base is there, and I think, again, in the future, it could be used for that, but it just hasn't been yet."
No. 8	At the beginning of the project, expressed a belief that FEA would "inspire confidence early in the design

Participant	Confidence in design
	[process] that we have something that's going to work." Described the perceived role of FEA of the electronics assembly in the overall product development process, aimed at establishing confidence that the design concept meets its functional requirements, stating that "We do have [FEA] in the qualification plan, but I don't think the FEA results are going to be spread widely in the community. It's more of an internal qualification, an internal reassurance, which is backed up by other tests as well." At the end of the project, stated that, "[FEA] definitely influenced my confidence, because Jerrod did share his results side by side with the testing results. Um, but in my role, it didn't really affect my engineering judgment at all. So, I would say, yeah, it definitely increased my confidence." Also revisited the stated scope or purpose of the FEA modeling,, stating "I would say I - at one of the reviews we supported - changed my mind a little bit, in the fact that we would like to use some of the FEA results to verify and validate our requirements. So it's going from more of an internal reassurance in our design work to showing our customers that, based on what I'm calling 'relative similarity' to past products, that our design is 'functioned' in that space a little better, and so we should be able to use that as proof that we've met our requirements. So that's ultimately what I'd like to do, but it's… we're still working on that."
No. 11	At the beginning of the project, identified two critical questions they would ask about the FEA results obtained on this project: "One, were any major weaknesses identified? And then the second would be, How well does the model compare to the actual test results?" These speak to confidence in the design, and confidence in the FEA, respectively. At the conclusion of the project, when asked to what extent the FEA influenced their confidence or engineering judgment about the design, remarked, "I think I looked at it more as a… well… a little bit, I mean. I relied more on the actual testing than the model. But, it did help a little bit. … I think the fact that the results for the most part matched the model, or were very similar to the model - I think that did give confidence." Also stated, "I mean, the design was a little similar to other designs, but not completely. So, yeah, I think we were a little confident going in, based on the previous design, but the FEA added even more confidence to that."
No. 12	At the conclusion of the project, when asked to what extent the FEA influenced their confidence or engineering judgment about the design, commented, "It only confirmed it after I looked at the test data. That's where I saw the comparison between the FEA results and the test, and that's where I felt very confident with the design."
No. 13	At the conclusion of the project, when asked to what

Participant	Confidence in design
	extent the FEA influenced their confidence or engineering judgment about the design, commented that "It was good to have just kind of another tool, to kind of point to how… I guess… to point to the design as we were making it, not knowing how it would function or how it would perform. Kind of being able to get a first-run approximation of, 'will it perform well? Yes, it looks like it will.' So, that kind of provided some confidence in going ahead and building hardware and doing testing, and kind of committing to some design decisions that we made. So, I guess, I would say it definitely provided a new level of confidence beyond just kind of a gut instinct, which was nice." Also stated that, "one advantage was having the FEA model was able to show where possible weak points were in our design. And so then we were able to kind of instrument and pay close attention to those areas when we did our actual testing. And so that gave us, I think, the most useful data out of our testing, which is beneficial for the design as a whole because you're able to test at the weakest points, and if those perform well, then you know that the system as a whole will perform well. So I think that's definitely an advantage."

Participant	Laboratory testing
No. 1	At the beginning of the project, made some interesting comments about the relationship between testing and FEA: "Were those differences from an issue with the testing itself, or are they an issue with the modeling? And so again, you have to know more about what's your setup, what is the right answer, because you don't want to sit there and go back to your FEA and force it to meet your test setup, when there might have been something wrong with your test setup, and the FEA analysis might be closer to the truth than your actual experiment." At the end of the project, expressed a general goal of reducing some testing by using FEA: "The advantages are going to be that, hopefully, with the testing, it will allow us to…possibly to expand out the FEA model to… you know, we may able to not do, possibly, some testing later on, and save some time and expense, if we make some good judgments on how well we can push the boundaries of the FEA model as it compares to what we saw from the testing." Also stated that: "Well, I think having confidence in your FEA results comes from testing and understanding your design, and I think, having the… the experience with your design to know how far to push your FEA model… A lot of it, I think, really depends on, then, the skill of the person that's doing the modeling, and how they apply that to the results of the testing."
No. 4	At the beginning of the project, articulated a view of the relative level of 'need' for FEA and testing: "The

Participant	Laboratory testing
	fact that the FEA results are dependent on your fidelity - my opinion would be that you wouldn't rely solely on the simulation results. You always need to run actual tests." And listed the following critical questions that they would ask regarding FEA results obtained on this project: "What is the fidelity of the model? Do the test results match the simulation results? And, do you understand the differences?" At the conclusion of the project, emphasized the importance of doing validation testing early on to build confidence in the FEA model. Also described the following advantage of using data acquired during testing of a first prototype to validate the FEA model. "I think there are some pretty good advantages, one being that we can't instrument the entire system in every location, and so the FEA - if it agrees at the locations we did instrument - we can trust it at locations that we couldn't instrument. So we can get ideas for levels that we would see on different locations on the boards, or other locations that we just couldn't instrument."
No. 7	At the beginning of the project, emphasized the importance of validating the FEA model with test data. "I think it's important to get an FEA model set up, and kind of set up early, and then kind of go through this initial round of testing, and see if you can validate any of those models in testing. And then, based on that, we could use it for, you know, a variety of things." "If we get, basically, trying to get FEA up as we go, and just make sure on these early testing, we get, or we validate at least some part of the model - maybe not necessarily all of it, but an interface between connectors and boards, or something, could be done. And I think the earlier we do that, maybe, the better we could utilize it for other changes later." "I think, in the end, it has to be based on some test data. I think if you can show that, you know, your model at least predicts some result in some testing accurately, or within the accuracy that you need, then I think that opens up a lot of doors. But I think if you can't answer that question - if you can't show that that matches up at all - then I will lose a lot of confidence in your model." During the case study, this participant used FEA modal analysis to design a test fixture to be as light and stiff as possible. At the end of the project, reiterated the importance of validation testing: "I do like how it sort of validates the model, and how we see the responses in the model be very similar to the responses in testing… Some sort of validation [is important], sort of like what we did here, where we have testing to compare to these FEA results - that we have similarity there."
No. 8	At the beginning of the project, mentioned several times the possibility of using FEA to reduce the amount of testing required: "[FEA is] going to be beneficial in

Participant	Laboratory testing
	the same way it was beneficial on the first project, which is using models early in the design to figure out what's going to work and what's not going to work, and be able to quickly make changes to the model and run these analyses and simulations instead of having to do it in a hardware scenario." "Having a confidence in the design early really allows for an aggressive schedule and paring down the amount of tests we need to prove our concept." "Can we use FEA analysis in lieu of testing, rather than a precursor to testing, if we feel confident enough in what we're getting, so we can save time and money?" By the end of that project, seemed to maintain that view, but articulated it much more elaborately. "I think internal to the team, I think it's pretty well accepted, but bringing it to outside people and showing that FEA is a valid approach is a little bit harder. … I think their concerns lie mostly in their lack of understanding of what's going on. And since we're dealing with multi-million dollar products - and possibly even more if there's failure - the customers really want to see every little thing tested throughout the project life cycle, and every little component tested, whereas our timeline and budget really doesn't allow for that. And so we're trying to use FEA as a substitute to say, 'You know, [we've used] something similar before, and based on our modeling, what we're [using] now is better, and so we really don't want to test that piece' - and so selling that idea to a customer, and them coming back and saying, 'No, we still want you to test everything, because failure is not an option.' And so trying to overcome that space is difficult."
No. 11	At the beginning of the project, mentioned the importance of validating FEA results with test data. At the conclusion of the project, basically reiterated multiple times how important it is that FEA results agree with test results. "Clearly, they would still have to do a real test, and compare it to the model, and show me similar results. And I think between those two things, I would be pretty confident in using the model for future design - for future aspects." "We're always going to have to do testing, so if we always have to… I guess it's good to always have a model too, but if it's one or the other, we're always going to have to do the testing, whereas we're not required to have the model, therefore if money is limited, or time is limited, clearly one is going to win over the other." Mentioned the possibility of reducing testing: "I don't ever see us being able to not test, so we're always going to have to do the testing anyway. But if there was time that we were confident enough in the models, or could prove that they were so good that we didn't need to test, then that would be extremely beneficial."
No. 12	At the conclusion of the project, emphasized that

Participant	Laboratory testing
	comparing the test data to the FEA was essential for building confidence in both the FEA and the design. "[FEA] only confirmed [design confidence] after I looked at the test data. That's where I saw the comparison between the FEA results and the test, and that's where I felt very confident with the design." Interestingly, suggested that always doing FEA first, before testing if possible, is preferred, to eliminate the potential for bias: "FEA was used to predict the responses first, and then it was correlated with the test data, and so that helps with the FEA. … I think, definitely, um, kind of creating an FEA model in parallel with the design work. Definitely have it done before, like, tests are done to correlate the results, because I've seen personally a lot of times where the testing results are used in order to make the model match the testing, but I've seen it done incorrectly in that way. So I think, um, if you have predictions to start with, and you correlate that with how the test is done, and looking to see how close they match, I think is probably the way to go."
No. 13	At the conclusion of the project, described how FEA was used to guide the experimental testing, e.g., for selecting the locations to monitor in the design. "One advantage was having the FEA model was able to show where possible weak points were in our design. And so then we were able to kind of instrument and pay close attention to those areas when we did our actual testing. And so that gave us, I think, the most useful data out of our testing, which is beneficial for the design as a whole because you're able to test at the weakest points, and if those perform well, then you know that the system as a whole will perform well." Cautioned against the tempting idea of using FEA without testing: "On its own, it would be a little dangerous to depend solely on an FEA approach to engineering. But if it's coupled with some actual testing or some, you know, other physical or kind of actual production engineering approaches, I think it can be very useful."

Participant	Design similarity
No. 1	Described this project as follows: "With… the Design Project No. 1, right, there was a great amount of similarity between the two. With Design Project No. 2, there was no similarity, other than… we could say there was similarity between this one and a completely separate project, but I'm not really looking at any information I've had with that other project as compared to this one. So this one is really looking at FEA analysis by itself, and comparing it to testing by itself, with no similarity to either Project No. 1, or really pretty much any other system that we have done before."

Participant	Design similarity
No. 4	Described this project as follows: "Well, um, we didn't have the luxury of using something that was… re-using a design, so this design was pretty new. So, um, I guess it wasn't much of a factor."
No. 7	Described this project as follows: "So, in the first project, there was that similarity. But I feel, in the second project, we didn't have a previous project which had as much similarity. So that wasn't as much of a factor. There were kind of loosely-similar designs, but I don't know… I kind of considered it brand new."
No. 8	Described this project as follows: "This seemed like an entirely new project, so design similarity was not a factor." Discussed an interesting topic of how designs that are similar to previous designs could utilize FEA, rather than prototype testing, to demonstrate that they meet requirements, but this this topic is a new one being discussed on the project. "I think [the customer's] concerns lie mostly in their lack of understanding of what's going on. And since we're dealing with multi-million dollar products - and possibly even more if there's failure - the customers really want to see every little thing tested throughout the project life cycle, and every little component tested, whereas our timeline and budget really doesn't allow for that. And so we're trying to use FEA as a substitute to say, 'You know, [we've used] something similar before, and based on our modeling, what we're [using] now is better, and so we really don't want to test that piece' - and so selling that idea to a customer, and them coming back and saying, 'No, we still want you to test everything, because failure is not an option.' And so trying to overcome that space is difficult." This is an interesting example of using various sources of design knowledge to build toward design confidence, where the triad of testing, FEA, and design similarity is 'split' differently than in many other instances.
No. 11	At the beginning of the project, when asked what factors might limit the effectiveness of using FEA on this particular project, stated that, "I think if the design is extremely similar to other designs that have already been tested, then the FEA might not be needed. You know, you might already be fully confident in the major aspects of the design, so I could see that being a limitation." So that is an example of design similarity and FEA being in tension with each other. At the conclusion of the project, when asked if design similarity was a factor for them on this project, simply replied, "yes." Later elaborated on this, remarking, "I mean, the design was a little similar to other designs, but not completely. So, yeah, I think we were a little confident going in, based on the previous design, but the FEA added even more confidence to that." When asked what things, if any, that have been learned on these two

Participant	Design similarity
	case study projects could be carried forward and applied on a future project, commented, "The only way I could see doing that would be if the design was similar. Maybe you could reutilize the same design because you know it already meets certain specifications, and you already have a model for it. So maybe you could try to tweak that model for whatever the new project is, and come up with a quick answer as to whether or not it will work." So that is an example of design similarity and FEA working together in a complementary manner.
No. 12	Described this project as follows: "For this project, it wasn't a similar design for me, so it gave confidence as a baseline for what existing responses would be in FEA, but to me it's only a baseline to be able to match and see what a new design is like." When asked what things, if any, that have been learned on these two case study projects could be carried forward and applied on a future project, commented, "You know what the inputs are to the design, and you've seen the responses, and in a future project, if it's a similar input, and you're just improving on the design, you have a starting point. … If you were designing something new, but based on something else - you can always do that analysis on the existing one because you know it works right now. … And you can use that as your baseline to start." In other words, this is speaking to using FEA to answer relative questions: does a proposed change appear to be better or worse for design performance. Rather than absolute questions: will a proposed design perform adequately or not.
No. 13	Described this project as follows: "For this project, it was a completely new mechanical design altogether. So it was very - there wasn't really much design similarity to go on. So I would say the amount of confidence gained from a similar design was negligible." "[FEA] definitely provided this project - being kind of a whole new mechanical design, with nothing really to look at and say, you know, 'based on this project, we know we're in pretty safe territory' - I think that having the FEA, or having FEA capability, provided us with a good amount of confidence in the design, at least on a qualitative level, which was I think very useful in shortening the design time and really developing a product that was, you know, very well designed right from the beginning, with our very first prototype." Several times, commented that from their experience on this project, it appears that FEA is most useful for brand new designs, in order to help bring into focus the potential weak or problematic areas in the design that should be paid special attention during design and testing. "Coming back to the idea of having a new, a completely new, mechanical design - I think that having the FEA model was really useful, to be able to kind of nail down where areas of concern might be, so you can focus your

Participant	Design similarity
	engineering effort in those areas." "I think that, based on this project, I'd probably be more likely to be an advocate for using FEA, especially, like I said, if you're working on a new design."

Participant	Role of the research investigator
No. 1	When asked how their view of the product design and/or the FEA was affected by the fact that the research investigator served both roles (design and FEA), stated that, "I think from my perspective, I have more confidence in the product design, since Jerrod used FEA, because again it backs up his initial design calculations or assumptions." Did not really make any further comments about my role on the project.
No. 4	When asked how their view of the product design and/or the FEA was affected by the fact that the research investigator served both roles (design and FEA), stated that, "I think it's a valuable tool for the designer to have an FEA model that's trusted… so I think it worked well to have Jerrod do both. I think it's a valuable tool for the designer." Did not really make any further comments about my role on the project.
No. 7	When asked how their view of the product design and/or the FEA was affected by the fact that the research investigator served both roles (design and FEA), offered no comments.
No. 8	When asked how their view of the product design and/or the FEA was affected by the fact that the research investigator served both roles (design and FEA), stated that "I think he does very good work, so both of them I'd say are probably done very well." Did not really make any further comments about my role on the project.
No. 11	When asked how their view of the product design and/or the FEA was affected by the fact that the research investigator served both roles (design and FEA), stated that, "For the product itself, it definitely gave greater confidence, because Jerrod is a thorough worker, and he's proven himself before, so it definitely helped. The FEA… it probably helped a little, because I know he takes everything he does seriously, but I'm not as familiar with FEA modeling in general, so it's kind of starting from scratch for me on that side of things. So while I know he's a good worker, I didn't have experience with that anyway, so it helped a little, but not as much as the actual design." So confidence in the analyst helped some, but was not a major factor for this participant.
No. 12	When asked how their view of the product design and/or the FEA was affected by the fact that the research investigator served both roles (design and FEA), stated that, "If he did the design, he knows the intricacies of trying to create the FEA model at the same time. A lot

Participant	Role of the research investigator
	of times what I see is one person does the design, and it's kind of farmed out for someone else to do the FEA, and that's where things can get lost because of, like, material properties, or how things get assembled together. So by doing both the design and the FEA, I think it really helped - and being very detailed in particular about it."
No. 13	When asked how their view of the product design and/or the FEA was affected by the fact that the research investigator served both roles (design and FEA), stated that, "I think the fact that he was kind of involved heavily in both, it added confidence for me in his FEA model, because he knew the product very well, since he was designing it. So he knew, kind of, some of the nuances behind it that might factor in to how he built the FEA model. So, I guess, him being very involved in the product definition and design provided confidence for me in the FEA model. And then the other way around - him getting feedback for himself from the FEA model to iterate on the design, kind of, brought confidence back into that itself. So, I feel like, working on both of them as one designer was pretty - I would say was pretty beneficial. They seemed to complement each other well."

Participant	Beneficial overall
No. 1	May have moderated their view ever so slightly. At the beginning of this project it was always "10" for every question. FEA was great in every regard. For this project, when asked how beneficial FEA was overall, replied, "It's going to be, depending upon how we wind up using it - what the specific circumstances may be, I don't know - but it will be definitely in the 8 to 10 range." When on to describe how the time required is still the most difficult limitation, and how much they learned about the time required.
No. 4	When asked how beneficial FEA was overall, replied "7 or 8. It was pretty good." But did not follow up with any additional comments.
No. 7	When asked how beneficial FEA was overall, replied "So far, I think we have a good base, but we haven't actually done anything with it, other than to show that, oh, hey, our model matches our test results. So as of right now, I'll have to say a 6. But hopefully in the future that number would go up as we have design changes that can be evaluated using the model that we have. It hasn't come up yet in this project, so its usefulness hasn't really shown itself." When on to describe how the time required is still the most limiting factor.
No. 8	When asked how beneficial FEA was overall, replied "8. I would say an 8." When on to describe how the biggest limiting factor selling it to the customer.
No. 11	When asked how beneficial FEA was overall, replied

Participant	Beneficial overall
	"maybe a 6 or 7… I think it helped the team learn about FEA, and introduce the group as a whole to FEA and how the results can match the model, and therefore the model can help you. But, I'm still not 100 percent sure it actually drove any design decisions, so, in that sense, I'm not sure it helped the design aspect." When on to describe how the biggest limiting factors are the need to perform the modeling even earlier in the design process, and the goal of eventually reducing or eliminating some prototype testing using FEA, which would be a huge benefit.
No. 12	When asked how beneficial FEA was overall, replied "6 or 7."
No. 13	When asked how beneficial FEA was overall, replied "I think it was good to do it - you know, it gave good results, you have the test data now to compare, you know that it's a good FEA model. I haven't really seen further use of the FEA model yet. It doesn't mean that I won't - I think that if it comes to that, it would be a great tool because you know that it's a good model to start with - but I haven't seen that happen yet. So I would say that, um, the option is out there right now in order to be able to do that, but I just haven't seen it used yet. I could very… I could see the potential for it in the future."

Participant	Assumptions and limitations
No. 1	At the beginning of the project, expressed strong overall support for using FEA, but also discussed the limitations of FEA at length. "It's not a panacea, it will not answer all of the questions, understand its limitations and its advantages." "I'm a proponent of, well, any modeling and simulation, and, you know, with the caveats of you must have a rudimentary understanding of your system and what you're trying to model and simulate, so that you can then make a hopefully informed decision on the results that you get back from your modeling." At the end of the project, when asked if there were any ways that they would want to see FEA used, or NOT used, on a future project, replied, "I would not want to see FEA used as the sole means of validating a design. It has its limitations, as all modeling systems do, so you need to be very careful with that. But I think - you know, keeping with kind of my theme all through the interview here - I'm a big proponent of it, and when used properly with analysis and testing, it's a tool that should absolutely be used on all projects."
No. 4	At the beginning of the project, noted that "It seemed difficult to figure out which features were critical to having a high-fidelity model and which features weren't. … You have to trade-off between which features you want

Participant	Assumptions and limitations
	to model and keeping the model simple, so that it's a quick simulation. So trying to figure out which features are necessary and which features aren't seemed like a challenge." Also noted that, "The fact that the FEA results are dependent on your fidelity - my opinion would be that you wouldn't rely solely on the simulation results. You always need to run actual tests." During the course of the project, there was some related work investigating the mechanical integrity of a sealed vessel under conditions of internal pressure. The end covers of the joint designs are sealed using a bolted joint and O-rings. This participant later asked the research investigator if FEA modeling could be used, rather than testing, to assess the structural integrity of the sealed joints. We discussed that while this is possible, it is more difficult to get reasonable accuracy out of this type of FEA modeling for several reasons: it involves stresses, not displacements/accelerations; plasticity of the metal parts; hyper-elasticity of the rubber O-rings; time involved to build the FEA model, etc. The participant brought up the possibility that we might be able to use the modeling effort to demonstrate than sufficient margin exists before you ever even hit those non-linear effects. That is true with regards to the yielding of the metal parts (and to some extent, perhaps the O-rings, if the displacements of the metal parts end up being small enough) and is a really clever thought. At the end of the project, when asked if there were instances where the limitations of FEA were especially evident, or where the assumptions in the FEA seemed problematic, replied, "If I recall, there was at least one instance - but I don't recall the specifics - but it seems like there was a case where we had questions about how well the model was representing the actual."
No. 7	At the beginning of the project, when asked what factors might limit the effectiveness of using FEA for this project, replied that time was probably the biggest limitation. Also stated that, "I think we may run into some issues where maybe some model doesn't agree with test results, and then, depending on if we use some, I don't know, weird material that responds differently, but I can't think of anything specific for that." At the end of the project, when asked if there were instances where the limitations of FEA were especially evident, or where the assumptions in the FEA seemed problematic, replied, "The main thing it doesn't do right now, is it still doesn't answer the question whether something will break or not. It kind of tells us the levels that we're going to see, and we don't have a way of saying, 'Is this okay? Is our sub-component going to survive this environment, given these levels?' So I think that's the main limitation we have, at least with the method that Jerrod is using. I think there might be other methods

Participant	Assumptions and limitations
	which are more time-intensive and require much bigger models that might be able to answer that. So that's kind of a limitation, and it's kind of a play with time and model size." When asked about the feasibility of using FEA on a project like this one, noted that, "We can get some basic answers from it, it can't answer everything, but I think we can use it for… We can kind of use it for what Jerrod kind of intended to, which is comparisons - making sure that certain design changes don't increase levels, or modes - there's peaks in the frequency response that we don't like to see, and if there are, we could figure out how to mitigate those, or say that they're low enough that we could deal with them. So I think it's definitely feasible for those kinds of questions. … Again, if it's like, 'is it going to break or not?' we have to use judgment on that, and it doesn't give us a straight answer on 'yes, this will work, no, it won't work.' So for the use that he is intending, it's a very high feasibility, but if you just want a yes or no answer, then it's not feasible basically."
No. 8	At the end of the project, when asked if there were instances where the limitations of FEA were especially evident, or where the assumptions in the FEA seemed problematic, replied, "No, I did not see any."
No. 11	At the end of the project, when asked if there were instances where the limitations of FEA were especially evident, or where the assumptions in the FEA seemed problematic, replied, "So, clearly he had to make some assumptions on things. Like sometimes, screws were modeled as a certain thing, or individual batteries were modeled as a huge chunk, and I think he did that to possibly save time on processing time, and I just don't know if that's a valid interpretation or not. Again, the results seemed to work, so it probably was. But whenever you do estimates like that, I kind of question it." Here the individual is referring to the simplified battery model (used for the shock analyses) in which the battery pack internals were modeled as one simplified mass.
No. 12	At the beginning of the project, when asked how they have seen the use of FEA fail to benefit, or even hinder, a project, replied, "Assumptions that convergence has occurred without checking. Incorrect boundary definitions leading to bad testing." Also described other important factors: "Understanding how the math behind how FEA works as well as a basic understanding of the problem one is using FEA to solve. Ensuring that the proper assumptions are also put in place as well as joints and contacts." At the end of this project, when asked about several of these specific concerns, said they were not an issue on this project. But still summarized their view of FEA as follows: "Uh, I still have mixed feelings about it. It really depends on the designer and the analyst. I think

Participant	Assumptions and limitations
	if the analyst and the designer know how to implement FEA correctly, then I would be a huge advocate for it. But it really comes down to trusting the person who is doing it.”
No. 13	At the end of the project, when asked if there were instances where the limitations of FEA were especially evident, or where the assumptions in the FEA seemed problematic, replied, “I think I just kind of come back to the fact that, you can have a pretty reasonable model, and it might not necessarily match exactly what’s happening in your system. And so I guess that kind of comes back to not solely depending on FEA, but using it as kind like a building block, or one of your design tools in your tool kit.”

Participant	Confidence in FEA
No. 1	At the beginning of the project, when asked to rate FEA in terms of being a legitimate engineering approach, gave it 10 points (on a 10 point scale). At the end of the project, when asked the same question, replied, “I think it’s definitely a legitimate approach, and how it’s used within the bounds of using test results for validation, I think it’s a 10. … The more I see FEA, and the more I see test data that corroborates what we’re seeing with the FEA model, yes, my confidence grows all the time. But again, a lot of it is going to be up to the engineer that is using it, and how he applies it.” When asked if their confidence in FEA increased as a result of this project, replied, “Definitely increased, yes.” Also elaborated: “I think having confidence in your FEA results comes from testing and understanding your design, and I think, having the… the experience with your design to know how far to push your FEA model on looking for an analysis and looking for results, before you decide that, ‘Hey, I’ve gone far enough. I now need to go back and re-do some testing with the changed design, or to higher limits, to see where the FEA model - how it compares to the testing.’ So a lot of it, I think, really depends on, then, the skill of the person that’s doing the modeling, and how they apply that to the results of the testing.”
No. 4	At the beginning of the project, when asked to rate FEA in terms of being a legitimate engineering approach, gave it 6 or 7 points (on a 10 point scale), commenting, “I think it’s worth the time, but it’s hard to get that time when you’re on a fast-paced project.” At the end of the project, when asked the same question, replied, “I would say an 8.” When asked if their confidence in FEA increased as a result of this project, replied, “Um… about the same.” Also, when asked what factors are important to them for building confidence in the FEA results, remarked, “In terms of building confidence -

Participant	Confidence in FEA
	yeah, just being able to validate the model with actual testing.”
No. 7	At the beginning of the project, when asked to rate FEA in terms of being a legitimate engineering approach, gave it 9 points (on a 10 point scale), commenting, “I’m not questioning its legitimacy at all. It’s kind of like anything - you kind of get what you put in. So if you put in legitimate work into it, I think you’ll get legitimate things out.” At the end of the project, when asked the same question, replied, “I think it’s a 10, I guess - a totally legitimate approach. It kind of just depends on how you use it, and I think we’re using it in a good way here. There’s nothing that replaces testing, but this is a good way to see whether some basic things can happen. It really depends on what you use it for, but it’s totally a legitimate engineering approach.” When asked if their confidence in FEA increased as a result of this project, replied, “I think it has slightly increased - just kind of seeing what Jerrod can come up with, even just on his own time, he can kind of - in the software he uses, how close he can get to some of the results without actually… even before validation, and fiddling with the model to fit his results. That was impressive. I am impressed how close the model came to the actual test results on the second project.” So although this participant seems impressed with the overall accuracy, the reservation in the answer makes it seem like something else is at play when asked about ‘confidence in FEA.’ Perhaps it’s time required? Or the usefulness of it? (Since several times they remarked how the model is good and accuracy is established but it has yet to be ‘used’ like it was on case study 1.)
No. 8	At the beginning of the project, when asked to rate FEA in terms of being a legitimate engineering approach, gave it 9 points (on a 10 point scale), commenting, “It’s high. I still think it’s a legitimate engineering tool.” At the end of the project, when asked the same question, replied, “I would probably rate it a 10. I think it’s a very valid approach, when used in conjunction with other engineering approaches as well. I wouldn’t say FEA is the only way to go, but I do think it’s very valid.” When asked if their confidence in FEA increased as a result of this project, replied, “Definitely increased - seeing the results of our testing compared to FEA.” When asked about the way FEA and testing were used in conjunction, remarked, “I kind of viewed how we worked as a necessity. Once we had results, we wanted to put them against our model for validity and accuracy of the model, and I think - I guess the advantage is we can now have more faith in the models moving forward, and in FEA in general.”
No. 11	At the beginning of the project, when asked to rate FEA in terms of being a legitimate engineering approach, gave it about 5 points or a little bit greater (on a 10

Participant	Confidence in FEA
	point scale), commenting, "I got to actually see it being used in a positive way." At the end of the project, when asked the same question, replied, "Ten. I mean, I think it's a good approach." When asked if their confidence in FEA increased as a result of this project, replied, "It increased slightly. … Because he did show a very strong correlation between the model and the product, and that always helps increase my confidence in something." When asked about the comparison to test data and the overall credibility of the FEA results, commented, "The results he showed mostly matched the model, at least to some degree. There were a few areas that were off, so that made me question what the difference was. I don't think that necessarily hurt - I did not lose any belief in the credibility of the overall modeling scheme. It was kind of on par with what I thought. It can help, but it's not perfect. … There were some spikes that were completely not aligned with the model."
No. 12	At the beginning of the project, when asked what factors affect their impression of the credibility of FEA results, replied, "My expected results from analysis / calculations," and also, "How realistic is the answer compared to a decomposed / simplified problem if possible." At the end of the project, when asked to rate FEA in terms of being a legitimate engineering approach, gave it 8 or 9 points (on a 10 point scale). When asked if their confidence in FEA increased as a result of this project, replied, "It hasn't increased or decreased. I think my confidence in it is based on the person who is doing the FEA analysis, not the analysis itself, because I've seen cases where the FEA can be wrong, but it's taken as the correct answer, or the correct method, and so, for me, it's really being able to trust the person who is doing the FEA analysis to make sure that it's a legitimate result." Also stated that, "[FEA] only confirmed [design confidence] after I looked at the test data. That's where I saw the comparison between the FEA results and the test, and that's where I felt very confident with the design."
No. 13	At the end of the project, when asked to rate FEA in terms of being a legitimate engineering approach, gave it 7 or 8 points (on a 10 point scale), commenting, "I think it's definitely very useful, but just kind of from the experience that I had on this project, it definitely can point out some… it can point out areas of concern, but it's not always… it doesn't always match how you test on your first run. And so I think, on its own, it would be a little dangerous to depend solely on an FEA approach to engineering. But if it's coupled with some actual testing or some, you know, other physical or kind of actual production engineering approaches, I think it can be very useful." When asked if their confidence in FEA increased as a result of this project, replied, "I'd

Participant	Confidence in FEA
	say, overall, it's increased, just being able to see how well Jerrod's FEA models did match with our actual test data. It was pretty cool to actually see how he was able to kind of predict where the weak points would be and to what level they would respond to the different vibration environments. And so that was pretty cool to see, and it kind of opened my eyes to the power, or the value that FEA can have."

Participant	The analyst
No. 1	Overall, this participant contrasted at length the two modes of working, one where the FEA analyst is on the product design team, and one where the analyst is in another group. No real change in opinion over the course of the study. At the beginning of the project, described how communication was improved because the person doing the FEA was on the design team and co-located in the same department and office area, and could easily get with other members of the design team. By the end of the project: "I think having confidence in your FEA results comes from testing and understanding your design, and I think, having the… the experience with your design to know how far to push your FEA model on looking for an analysis and looking for results… So a lot of it, I think, really depends on, then, the skill of the person that's doing the modeling, and how they apply that to the results of the testing." Again: "The more I see FEA, and the more I see test data that corroborates what we're seeing with the FEA model, yes, my confidence grows all the time. But again, a lot of it is going to be up to the engineer that is using it, and how he applies it." Again: "It can definitely, I think, again - depending upon the complexity of the models and, really, the answer that you're trying to get, or what questions have been raised - could simply demand that a lot more time be placed on modeling and a lot less time on getting some other part of the design work done, in which case then you'd want to sit down and consider: do we need to bring somebody else in to either allow Jerrod to work more full time on just the modeling and analysis, and let somebody else do the design work, or vice versa."
No. 4	At the end of the project, when asked about having the same engineer do both the product design and the FEA, remarked, "I think it's a valuable tool for the designer to have an FEA model that's trusted… so I think it worked well to have [the same person] do both. I think it's a valuable tool for the designer." Also pointed out that, in general, it's important to have "the time and funding to make sure that the FEA model isn't left by the wayside or abandoned."
No. 7	When asked about having a full-time person devoted to

Participant	The analyst
	performing FEA modeling for the product development team, commented that, in order to have confidence in the FEA results and a real impact in the design process, "I think a lot of it would be, if it's a full-time person, they would have to know the project. I think that's very important. Some sort of validation, sort of like what we did here, where we have testing to compare to these FEA results - that we have similarity there. And then being able to kind of quickly turn that around - with someone full-time, hopefully that's very possible. Yeah, and that way… That person - whoever does it - has to be integrated in the team, basically, or at least know the product well. I think that's the biggest factor in confidence in the results." Also later stated, "I think I would continue to want to see it used how it's used right now. I think it's working. It's not… It doesn't seem like it bogs down anyone too much at the moment. We don't have a full-time person working on it that's kind of separated from the group. So I think I like where this is currently going."
No. 8	At the beginning of the project, remarked that "[FEA] is feasible. … But I would caveat that with saying you need the proper resources. You need someone like [the research investigator] to be able to do it." At the end of this project, noted that, "The fact that Jerrod did both [design and FEA], I believe, helped our project, because he was able to answer his own questions very quickly about how small changes in design - he would run it through his FEA model and say, 'Yeah, this is a good change' or 'this is a bad change.' Uh, I guess what I didn't like about it is kind of a singular point of design, there wasn't really any diversity of thought. So, what if Jerrod didn't think through everything? You know, was he testing for everything appropriately? But for the most part, I trust Jerrod, so I'm very, very positive on his work product. So I'm confident in both." But also noted one of the main disadvantages that comes with spreading the work over a larger team: "I think the biggest factor for me would be how well they integrate into the design team and our testing team. Either if it's one person - Jerrod - or if we have someone full-time modeling, I would like them to be intimately involved in kind of how our team structure is set up. And so, the main part would be to break down communication barriers that could exist between FEA modeling, design, and testing of the design and models, which there are no barriers now, because Jerrod does all three. But if we did separate these functions, making sure that they are one team and they can all get the right information at the right time would be my biggest concern."
No. 11	At the end of the project, when asked about Jerrod do both the product design and the FEA, seems to have interpreted the question as focused on 'Jerrod' rather

Participant	The analyst
	than 'the same engineering doing design and FEA', and remarked, "on the product itself, it definitely gave greater confidence, because Jerrod is a thorough worker, and he's proven himself before, so it definitely helped. The FEA… it probably helped a little, because I know he takes everything he does seriously, but I'm not as familiar with FEA modeling in general, so it's kind of starting from scratch for me on that side of things. So while I know he's a good worker, I didn't have experience with that anyway, so it helped a little, but not as much as the actual design." Also, regarding the idea of in the future having a person devoted full-time to performing FEA for the product development team, that in order to have confidence in the FEA results, that an important factor would be "I think probably the person's experience using FEA, and doing that kind of modeling."
No. 12	Overall, this person emphasized repeatedly the importance of confidence in the person performing the FEA. At end of the project, when asked about having the same engineer do both the product design and the FEA, remarked "It didn't affect my view at all, only because if he did the design, he knows the intricacies of trying to create the FEA model at the same time. A lot of times what I see is one person does the design, and it's kind of of farmed out for someone else to do the FEA, and that's where things can get lost because of, like, material properties, or how things get assembled together. So by doing both the design and the FEA, I think it really helped - and being very detailed in particular about it." Again: "I think early on, it's going to be very important that the FEA analyst and the design engineer work very closely together, so that as changes are made in the design, the FEA person can also make those changes. It has to be very well coordinated. Also, it's got to be done in parallel because a lot of times we can't wait for the design to be done and then create an FEA model, because it takes time away from the schedule. So it has to be completely integrated in order to make a real impact." Again: "I think my confidence in it is based on the person who is doing the FEA analysis, not the analysis itself, because I've seen cases where the FEA can be wrong, but it's taken as the correct answer, or the correct method, and so, for me, it's really being able to trust the person who is doing the FEA analysis to make sure that it's a legitimate result." Again: "I still have mixed feelings about it. It really depends on the designer and the analyst. I think if the analyst and the designer know how to implement FEA correctly, then I would be a huge advocate for it. But it really comes down to trusting the person who is doing it."
No. 13	Overall, this participant made several comments which in one way or another emphasized the importance of the analyst and their role on the product development team. At end of the project, when asked about having the same

Participant	The analyst
	engineer do both the product design and the FEA, remarked, "I think the fact that he was kind of involved heavily in both, it added confidence for me in his FEA model, because he knew the product very well, since he was designing it. So he knew, kind of, some of the nuances behind it that might factor in to how he built the FEA model. So, I guess, him being very involved in the product definition and design provided confidence for me in the FEA model. And then the other way around - him getting feedback for himself from the FEA model to iterate on the design, kind of, brought confidence back into that itself. So, I feel like, working on both of them as one designer was pretty - I would say was pretty beneficial. They seemed to complement each other well." Again: "the FEA designer would need to have a very good understanding of the product itself and the nuances behind it, and some of the details that go into the actual design of the product. I think that if they don't understand it very well, then they can't provide meaningful analysis as to what may be sensitive, or what components may fail or not, based on, just different details. So that would be one thing, is to have a very good working understanding and a close relationship with whoever the mechanical designer would be. And then also, just being able to kind of loop back their output to that designer in order to provide feedback for, you know, ideas of where some weak points may be and how to possible mitigate those issues." Again: "I guess this is true of any engineering tool - but if you have someone competent to do the work, um, I think that it can be really useful and can really shorten your design cycle by kind of starting off with something that's pretty well understood."

Participant	Feasibility
No. 1	1st interview: end rating was a 10. 2nd interview: 8 to 10 range. So a little moderation of strong endorsement seen early on. Also caveated their answer in terms of future/general applicability, saying, "Our models right now have been such that it hasn't, I think, been an impact, at least from my perspective. But as the models get more detailed - if we decide to go that route, where we decide we need to have more detailed models - then my opinion might change. But I think right now it is not that much of a limiting factor."
No. 4	1st interview: end rating was a 7 or 8, and commented, "I can see the value in it. It does help the designers make decisions before, you know, actually cutting metal and having the parts made, so I can see the value in that." 2nd interview: 7 or 8, stating, "It seems pretty feasible for the way we do business." So no change.
No. 7	1st interview: ended at something "slightly more

Participant	Feasibility
	feasible" than the initial rating of a 5, and commented, "Looking at it now, I'm happy with the results we got from this initial FEA study [on case study 1], so now I see it as slightly more feasible." 2nd interview: 8 or 9. Elaborated "It's very feasible, we can get some basic answers from it, it can't answer everything, but I think we can use it for… We can kind of use it for what Jerrod kind of intended to, which is comparisons - making sure that certain design changes don't increase levels, or modes - there's peaks in the frequency response that we don't like to see, and if there are, we could figure out how to mitigate those, or say that they're low enough that we could deal with them. So I think it's definitely feasible for those kinds of questions. … Again, if it's like, 'is it going to break or not?' we have to use judgment on that, and it doesn't give us a straight answer on 'yes, this will work, no, it won't work.' So for the use that he is intending, it's a very high feasibility, but if you just want a yes or no answer, then it's not feasible basically.
No. 8	1st interview: ended at something "definitely greater than" a 4, and commented, "It's been done - it is feasible. Um - but I would caveat that with saying you need the proper resources. You need someone like Jerrod to be able to do it." 2nd interview: 10, "because we have done it," and when asked if FEA was able to keep up with the project, commented, "I would say yes, although I know Jerrod is a very busy man. So I think he used FEA in a very smart way - probably more could have been done - but I think he's thought through what answers he wanted from the model, and went in that direction. So… so yeah - I think he was able to keep up with himself."
No. 11	1st interview: end at something "greater than" a 4, commenting, "because I saw that they could do it within the design process and help -- use it to help guide decisions." 2nd interview: 9, commenting, "I mean, it's completely reasonable to expect them to use it on future projects."
No. 12	At the end of the project, rated feasibility as "very feasible," and commented, "I think it's very good to do. Um, on bigger scale projects it may be a little harder, just because of the complexity. With complexity you add more variability. So I think for something of this size, it was a great use of the tool."
No. 13	At the end of the project, rated feasibility as 9 or 10, commenting, "I think it really depends on the engineer who is doing the work. If they're very competent with FEA, like on this project, I'd give it 9 or 10. It can work relatively seamlessly with the design, as long as you have someone who's well-integrated in the project and knows what's going on and can kind of keep up with the latest design decisions. So, you know, it depends on the engineer, but I think that it can be… it's definitely a feasible option and a useful tool." When

Participant	Feasibility
	asked if FEA was able to keep up with the project, "Yeah, I think for the most part it was. There was… I think that was helped by the fact that we got delayed a little bit, um… due to other things. But in general, I think Jerrod did a good job kind of keeping the FEA accurate and up-to-date, and then when, you know, once we did testing he was good about comparing the results to his model, and he gave a good presentation with those results. And, yeah, I think it was able to keep up pretty well."

Participant	Communication
No. 1	At the beginning of this project, expressed strong support for having the FEA analyst on the design team, citing improved communication. "Jerrod… is just right down the hallway, and so it's very easy to keep a very close communication link going, and that kind of goes back to your previous question - if you've got somebody in another group that is not… you know, it makes it much harder to have daily contact to just go in and say, "How are things going? What are the issues?" So I'm a big proponent of what Jerrod is doing and particularly with the fact that it is located within our own project." Again: "Jerrod being on the design team, co-located with everybody else, so that he can get with the electrical designers on how they're laying their boards out, he can get with other mechanical engineers and designers on other parts of the system. So, again, it's an integrated part of our team, it's integrated into our design processes." At the end of the project, when asked about how communication about FEA results could be improved amongst the members of the product development team, replied, "I think it's mainly, you know… you just are going to have to carve out the time to get everybody together and show the plots, talk about the information, talk about what you saw with the testing versus your modeling. It's simply making the time to do it. … And you know, we're all very busy, and so… it's just forcing the time and getting everybody together to go over the results."
No. 4	At the beginning of the project, stated that communication had gone well on the previous project (case study 1), but beyond that, did not elaborate on the topic of communication. Similarly, at the end of this project, did not really volunteer any thoughts on how communication about FEA results amongst the product development team members could be improved.
No. 7	At the beginning of the project, described communication on the first case study project as good overall, particularly in the area of being forthcoming with details about the FEA models. "I feel like if I wanted to really delve into the details - I didn't at this

Participant	Communication
	point - but if I wanted to, I could ask Jerrod, basically, and get all the kind of nitty-gritty models and things. I never felt like he was hiding anything from us, I guess. That kind of was my concern… is that things could be manipulated or hidden. And I think a very good job was done on this project of kind of just laying it out there, and if something's off, you know, you just kind of say, 'it's off,' and don't try to sweep it under the rug." Regarding the present design project, simply stated, "I think he's doing okay at what he's doing right now, just kind of presenting them at meetings and when they're relevant. I have no suggestions there." But later offered up a really interesting suggestion for helping to spread the use of FEA (think: Diffusion): "It is nice that Jerrod's doing all of this, but hopefully he finds a way to kind of transfer his FEA knowledge, I guess, because… I know he did hold like a bunch of little seminars or something years back, just kind of about FEA basics, but it would be nice to see how he modeled it, why he modeled it, maybe some, you know, things that worked for him, things that didn't. I don't have a lot of knowledge on the details of those - the very intricate, you know, 'how did you mate this surface to this surface' and 'what's your boundary condition here.' It's like, 'oh, actually, for this type of screw I found that this boundary condition works well because it takes a lot less time but it gives similar results.' So getting those little details passed on to new engineers, especially if we're going to be the ones kind of doing it - you don't have a kind of FEA expert doing it, and it's going to be in the engineers hands - you have to teach the engineers to do it. And I'm picking up a little of it, but that's kind of just by forcefully asking him. So yeah - something of that nature, something informational. I don't know whether he's going to write a paper on his methods, or what."
No. 8	At the beginning of the project, described communication on the first case study project as okay, simply stating, "I got all the information I needed out of it." Regarding the present design project, stated that communication about the FEA could be improved with customers and external stakeholders. "I think the product development team was very well informed of the analysis and the work that was being done. But like I mentioned earlier, in a similar situation, I would probably try to get the customer and next-level assemblies involved a little bit earlier, and try to get their buy-in before the work is being done, rather than showing them results and trying to get buy-in afterwards." Also emphasized the importance of communication if the roles of design engineer and FEA analyst are ever split. "I think the biggest factor for me would be how well they integrate into the design team

Participant	Communication
	and our testing team. Either if it's one person - Jerrod - or if we have someone full-time modeling, I would like them to be intimately involved in kind of how our team structure is set up. And so, the main part would be to break down communication barriers that could exist between FEA modeling, design, and testing of the design and models, which there are no barriers now, because Jerrod does all three. But if we did separate these functions, making sure that they are one team and they can all get the right information at the right time would be my biggest concern."
No. 11	At the beginning of the project, described communication on the first case study project as okay, simply stating, "It seemed like Jerrod did pretty good presenting his results to the team." At the end of the present design project, did not have any suggestions for improving communication about FEA results, stating that, "Jerrod seemed really proactive about giving presentations and showing the results of the models versus the testing, and just the models in general."
No. 12	At the end of this project, when asked to think about a future project where someone had a full-time job of performing FEA modeling for the product development team, emphasized the importance of communication: "So I think early on, it's going to be very important that the FEA analyst and the design engineer work very closely together, so that as changes are made in the design, the FEA person can also make those changes. It has to be very well coordinated."
No. 13	At the end of this project, when asked to think about a future project where someone had a full-time job of performing FEA modeling for the product development team, emphasized the importance of communication: "The FEA designer would need to have a very good understanding of the product itself and the nuances behind it, and some of the details that go into the actual design of the product. I think that if they don't understand it very well, then they can't provide meaningful analysis as to what may be sensitive, or what components may fail or not, based on, just different details. So that would be one thing, is to have a very good working understanding and a close relationship with whoever the mechanical designer would be. And then also, just being able to kind of loop back their output to that designer in order to provide feedback for, you know, ideas of where some weak points may be and how to possible mitigate those issues." When asked for any ideas on how to improve communication about FEA results amongst the product development team members, remarked, "I think that's kind of a hard one. Just thinking back to the presentation that Jerrod gave - I mean, it was very useful and very interesting to see, but it's… you know, there was just a lot of charts and graphs, and unless you take the time to kind of sit through and look

Participant	Communication
	them and take a little bit of time to understand the model setup and the testing setup and everything, it can kind of be lost on you. But I think… and I think also that that information is at different levels it has different benefits, I guess, to different people in the project, so I think the presentation that Jerrod gave, it was a good level of appropriateness. Our team, our whole team, kind of attended it and we were able to see how our product performed, and then he made that presentation available to other people who are involved with our product, just for their reference. But yeah, I guess that's kind of that is maybe one thing that's kind of hard to communicate, is how effective was your model in predicting the response of your system, because it's more complex than just saying - giving a percentage like, 'oh, it was 98 percent correct," or, you know… there is much more to it than that, so it's hard to sum it all up."

Participant	Accuracy
No. 1	At the beginning of the project, expressed the view, "Well, you know, accurate is… it's almost like, alright, define accurate? What is your… if you're within 10 percent, or 2 percent, or whatever?" At the end of the project, when asked about their impression of the accuracy of the FEA results, remarked, "I'll caveat that I'm an electrical looking at some of those plots, and so I may not be seeing all that Jerrod would see, or a mechanical analyst would see. But in some of the plots, the data that was taken from testing and then the results of the FEA were just aligned right on top of one another. I mean, I was very impressed with the results of the FEA as compared to the results from our testing."
No. 4	At the end of the project, when asked about their impression of the accuracy of the FEA results, remarked, "My impression was that the accuracy was pretty good, very good."
No. 7	At the end of the project, when asked about related topics, elaborated on their view of the accuracy for this project: "Just kind of seeing what Jerrod can come up with, even just on his own time, he can kind of - in the software he uses, how close he can get to some of the results without actually… even before validation, and fiddling with the model to fit his results. That was impressive. I am impressed how close the model came to the actual test results on the second project. … I was pleasantly surprised with the accuracy of this model. I think there were a couple nodes, or spots where the measurement was taken, that were different from testing. I think it was in only one spot actually. And that's something to look into, but everything else on the whole - I was pleasantly surprised with it."

Participant	Accuracy
No. 8	At the end of the project, when asked about their impression of the accuracy of the FEA results, remarked, "My impression is, they were accurate enough to make engineering decisions from - so, a 'good enough' answer."
No. 11	At the end of the project, when asked about their impression of the accuracy of the FEA results, remarked, "It looked really good. I would say 90 percent of it was in-line with testing results, and just a few things here and there that seemed off-kilter. So I was impressed."
No. 12	At the end of the project, when asked about their impression of the accuracy of the FEA results, remarked, "I think it was very accurate. Um, the results matched up very well with the test data. I think it's within the error of what an FEA can predict, and so I think it was very good. There was only one area which I saw that didn't match. There's possible explanations for it. But again, for the amount of testing that was done and the instrumentation that was used, for just one area to not match I think is very, very good." It is likely that the participant is referring to the inaccuracy at the edge of third (smallest) enclosed circuit board.
No. 13	At the end of the project, when asked about their impression of the accuracy of the FEA results, remarked, "I was - I wouldn't say surprised, but maybe impressed - with how well the FEA results kind of matched our testing. There were a couple instances where there were discrepancies, but in general, I think the FEA model definitely pointed out pretty accurately the problem areas in our design, and it didn't exaggerate or underestimate the… I guess, the responses that those areas would have to the different environments that we subjected them to. So, I think… I mean, I was impressed overall."

Participant	Time required
No. 1	Overall, describes time required for FEA as a balancing act that needs constant attention. At the beginning of the project, when asked if FEA keeping up would be an issue, commented, "Only if we can make sure that Jerrod himself does not get overloaded, because he's the principal engineer with doing that modeling and simulation, plus he has a lot of other work that he's trying to get in. So I think it's going to be just an overloading of Jerrod's time." At the end of the project, remarked, "From a project management perspective, I see how much initial time and effort that needs to be put into developing the models and everything. That's not a trivial amount of time, it's certainly not a trivial amount of time depending upon the type of analysis run that you're doing on the computers and all that. So, one simply needs to make

Participant	Time required
	sure that you factor that into your scheduling and your budget. You may want to, in fact, decide that you want to go out and higher a single engineer just to do the analysis. So, it depends upon the circumstances, but yes, it's given me a much better idea of just the time and effort that's needed to do all of this." Identified time required as the biggest factor preventing FEA from being even more beneficial. "Probably, uh, right now, it's the amount of time it simply takes to, in some cases, develop the model and run the simulations, but I think that's a pretty minor limiting factor. As I said, you know, on the previous question, Jerrod has got another computer to do a lot of that, so right now it's more taking up… he's got to take time away from either running tests, or doing other design work to set up the models. But again, I don't really look at that as a limitation at this point." Reiterated that view, stating, "I think things may get a little bit tighter in the future, but at this point, there was not a problem with the FEA keeping up with the project."
No. 4	At the beginning of the project, stated that "time and budget" might limit the effectiveness of FEA on this project, because "the schedule is pretty tight," and that there could potentially be issues with FEA keeping pace with the design activities. Also commented, "That seems like the biggest challenge with FEA keeping up with the design process, is just trying to fine-tune the model as you go along. … I think it's worth the time, but it's hard to get that time when you're on a fast-paced project." At the end of the project, felt that view was confirmed, "Time was definitely an issue for this project. Jerrod's been busy, but I think he was able to spend some time on the FEA models. But yeah, definitely time is a problem; budget, not so much." When asked about the possibility in the future of having one person dedicated full-time to doing FEA modeling for the design team, said that in order for FEA to have a real impact in the design process, "Starting the model early on, and doing validation testing early on, so that it can leverage those results for the actual design. And then, having the time and funding to make sure that the FEA model isn't left by the wayside or abandoned."
No. 7	At the beginning of the project, when asked what factors might limit the effectiveness of FEA on this project, replied, "I think a big one might just be time - just time that we have to spend on it, depending on how many other things are going on, because I know our schedule is packed, basically. That might actually be the biggest kind of factor in limiting its effectiveness." At the end of the project, felt that view was validated, stating, "I think time might be a factor. Jerrod is busy with a lot of things and I think there could be things… The models - although they're smaller than a lot of the other models that have been around, like the big system

Participant	Time required
	models and what-not - it does seem like it does still take some time to run them. So I think he is discouraged from running them for smaller issues, just because of this time factor. He doesn't have the time to do it, he doesn't have the time to wait for the results to come back. It's quicker just to either to test or, you know, build it into the design and - by kind of engineering intuition - say 'this isn't a big change, it will probably be okay.' Whereas, if there was more time, I think some of the smaller design decisions might actually be integrated into this FEA, if we had someone maybe full-time on it or something like that." When asked to identify one factor that prevents FEA from being even more beneficial, came back to this topic: "I think, again, it's that run time. So you know, if these could run in 40 minutes, you know, instead of 40 hours, that's something which we would do much, much more often. But, it does take some time, so it's done less." Looking to the future, remarked, "The schedule is tight in the next year or so, couple months or so - and we'll see if it's able to keep pace then. But I haven't seen anything to make me think that it's not feasible or that it won't work at this point. … I don't know what his total time added up to building this model is, but it didn't seem like it was all he was doing for that period of time. It seemed like he was getting other work done as well. Especially if we can use it in the future, to answer design questions - I think that will actually save time rather than hurt us. It all depends on the project."
No. 8	At the beginning of the project, was expecting FEA to actually speed up the project: "I think that it's going to be beneficial…using models early in the design to figure out what's going to work and what's not going to work, and be able to quickly make changes to the model and run these analyses and simulations instead of having to do it in a hardware scenario. So I think it's going to speed up the project. … Having a confidence in the design early really allows for an aggressive schedule and paring down the amount of tests we need to prove our concept." Followed this up with a thought: "If the results found in project 1 can be accurately matched to the testing we do in project 1, can this design model in project 2 be used to reduce some of the testing that we're going to need. Or, can we use FEA analysis in lieu of testing, rather than a precursor to testing, if we feel confident enough in what we're getting - so we can save time and money." At the end of the project, stated they did see FEA help with speeding up the project and building confidence in the design. When asked at the end of the project if FEA had been helpful for reducing the number of tests that had to be performed, stated, "It's still undetermined. Like I said before, we're definitely trying, and I think ultimately

Participant	Time required
	it will be, because we'll run out of time and money and have to fall back on some answer, but we're still in the process of getting that buy-in."
No. 11	At the beginning of the project, when asked if there might be issues with FEA keeping pace with design activities on this project, stated, "I may be wrong, but it was my perception that coming up with the models is a little time-consuming, and so I think the design could move faster than the modeling could. So I could see that being a limitation." At the end of the project, made several comments about time required for FEA. "I don't know how long it took him to develop the model, so I can't speak to that. I do know that running one version of his model seemed to be fairly reasonable, and was not a big deal, but one aspect was insanely long - one test he ran was something like 600 hours. So, that is completely unreasonable to have it be able to be impactful. I guess it all depends on how it's been modeled and what tests you're running - what simulation you're trying to run." Also recognized the external motivation by the researcher to complete this FEA work. "I think it kept up because Jerrod was really focused on doing it, and because he was doing it also as kind of his school work. If he just had to - if he hadn't had that as a purpose, it may have fallen to the wayside because of priorities - not necessarily because we didn't think it would be useful, but because if you felt crunched for time, and you're going to test anyway, you might say the model is not as important."
No. 12	At the beginning of the project, when asked whether FEA tends to lead, keep pace with, or lag design activities and decisions, replied, "Lag. Most of the design is complete based on quick analysis/calculation, and many times the FEA is done afterwards to see the overall result." At the end of the project, stated that FEA was able to keep up on this project, and when asked about using it on future projects, remarked, "It's got to be done in parallel [with design] because a lot of times we can't wait for the design to be done and then create an FEA model, because it takes time away from the schedule. So it has to be completely integrated in order to make a real impact."
No. 13	No data on views at beginning of project. At the end, noted the length of time required. "Comparing the test data to the FEA data - and maybe it's not so much of a disadvantage - there's just kind of a time lag there that you kind of need to adjust the model to really represent, or show, what was happening in the system. So that time delay - there's not much you can do about it obviously, and I guess it's better than having nothing - to be able to say, 'Yeah, actually the model does actually fit what we saw.' So maybe it's not so much of a disadvantage." When asked, replied that FEA was able to keep up with design activities, and further

Participant	Time required
	commented, "Another thing is just the time it takes to actually run the models. That's just a fact of life… but I think that's… I think a lot of people kind of, you know - there is quite a bit of a time in investment in doing it, and if you're not able to do it quickly, then I think people kind of turn away from the idea altogether." Finally, noted that FEA can actually help a project in terms of schedule: "Coming back to the idea of having a new, a completely new, mechanical design - I think that having the FEA model was really useful, to be able to kind of nail down where areas of concern might be, so you can focus your engineering effort in those areas, as opposed to, you know, kind of guessing - or making, you know, kind of educated guesses, but - I think it helps to focus your energy, which is… I think that's crucial to getting a good design out in a reasonable amount of time."

Participant	Dollar cost
No. 1	At the beginning of the project, this participant had the view that having the FEA capability within the design team was the most cost-effective. "One of the things that we have typically done at Sandia - and I suspect there might even be at a lot of other companies, also - is that you tend to have a group of people off in another department or division, and their sole job is to do this type of work. So if you're off funding somebody else, it's generally going to cost you a lot more money that if that capability is located within the project and design team." Very early on in this project, this participant proposed to the research investigator and to participant no. 8 the idea of budgeting for thermal analysis on this project, and then re-broached the subject on multiple occasions. In the end, we did pay for another analyst to perform thermal modeling. At the end of the project, when asked whether FEA dollar cost was an issue on this project, "On this project, not an issue at all, mainly because Jerrod has been doing the FEA modeling and analysis, along with other design work. If we had to, say, go to buying time on some of the supercomputers, paying for someone else to do all of this work, that may be a factor, but I would suspect that that's still going to be low enough on my budget line that I would still probably say, if it's a factor, it becomes a very minor factor. I would still be pushing for the FEA models and analysis."
No. 4	At the beginning of the project, did name budget as one area of concern that might limit the effectiveness of FEA on this project. At the end, said that they were not too aware of how much money had been spent on the FEA modeling, but that they didn't think budget was as much of a problem as time.

Participant	Dollar cost
No. 7	No data on views at beginning of project. At the end of the project, when asked if dollar cost of FEA was an issue on this project, stated, "It didn't seem like it. It seemed like the project had more money… it's more of a time, like a people-time, rather than dollars."
No. 8	No data on views at beginning of project. At the end of the project, when asked if dollar cost of FEA was an issue on this project, stated, "Uh, it was not an issue." When asked to think about using FEA on a future project, and if there were any ways they would or would NOT want to see FEA used, stated, "If it's applicable, I would like to see FEA used in a very similar method, where we use it to help make early engineering decisions, um, and also adding the extra piece that I would love to see modeling and simulation more used to prove requirements. I think that would save time and money overall on a project." So mentions the possibility of saving money using FEA.
No. 11	No data on views at beginning of project. At the end of the project, when asked if dollar cost of FEA was an issue on this project, stated, "I guess I would say negligible, but that may be an uninformed answer." When asked whether they would be an advocate or skeptical of using FEA on future projects, went on to describe their reservations with FEA. "I wouldn't be *more* skeptical. I think I'd be maybe a hesitant advocate, because I would like to use it, but it would all be based on time and money. … So I would like to use it, and I would like to see it be useful, I just don't know if our atmosphere is receptive to that. … We're always going to have to do testing, so if we always have to… I guess it's good to always have a model too, but if it's one or the other, we're always going to have to do the testing, whereas we're not required to have the model, therefore if money is limited, or time is limited, clearly one is going to win over the other. … While I'm not more skeptical, and I'm a little bit more of a believer, I just don't know if I could get it to be important in other people's minds who could control the money." So money (along with time) is still a strong limiting factor in this person's mind.
No. 12	No data on views at beginning of project. At the end of the project, when asked if dollar cost of FEA was an issue on this project, stated, "I can't answer than one, I have no idea."
No. 13	No data on views at beginning of project. At the end of the project, when asked if dollar cost of FEA was an issue on this project, stated, "I don't have a very good idea of that. It's pretty transparent to me, so I'll have to pass on that one."

Participant	Learning process
No. 1	Overall, this person clearly sees the process of using FEA in our product design activities as a learning process. At the beginning of this project, remarked, "I think what we necessarily have learned of FEA on the first [case study] project might not necessarily directly transfer, or translate, over to the second [case study] project because the designs are so significantly different. But, it's the whole idea of working on the FEA itself, developing the models, developing a process for doing it, starting to understand how much time and effort is need to develop the models, to do the simulations and the computer time and all of that. That's where what we did on the first project, I think, really will have an impact on the second one, as we get it folded into the design and our testing and qualification activities. … I think it's all a learning process, and that it's something we as a team want to do." At the end of the project, reflected back and compared the two case study projects. "With the first project, things were… We had a design, components in that design had already gone through a lot of testing, it was a known entity, it was already being used in product, if you will. So, I think as far as the first design goes, it was… the results of the FEA were used to simply confirm what we pretty much already knew, plus also get Jerrod - not necessarily 'up to speed' - but get us going down the method of using FEA in our design. Now, as it applies to the second design, now we're in brand new territory. So now, it's not that we want to call in question the results of the FEA, we simply now want to do the testing to validate the FEA." No other substantial comments about the learning process.
No. 4	No real data indicating views of using FEA in product development as a learning process. When asked, did not offer any suggestions on how to take things learned on this project and leverage it forward to future projects.
No. 7	When asked for ideas on how to take things learned about FEA on this project and leverage it forward to future projects, replied, "It is nice that Jerrod's doing all of this, but hopefully he finds a way to kind of transfer his FEA knowledge… I know he did hold like a bunch of little seminars or something years back, just kind of about FEA basics, but it would be nice to see how he modeled it, why he modeled it, maybe some, you know, things that worked for him, things that didn't. I don't have a lot of knowledge on the details of those - the very intricate, you know, 'how did you mate this surface to this surface' and 'what's your boundary condition here.' It's like, 'oh, actually, for this type of screw I found that this boundary condition works well because it takes a lot less time but it gives similar results.' So getting those little details passed on to new engineers, especially if we're going to be the ones

Participant	Learning process
	kind of doing it - you don't have a kind of FEA expert doing it, and it's going to be in the engineers hands - you have to teach the engineers to do it. And I'm picking up a little of it, but that's kind of just by forcefully asking him. So yeah - something of that nature, something informational. I don't know whether he's going to write a paper on his methods, or what." This is really interesting -- basically this person supporting efforts to diffuse detailed information on how to use FEA to the design engineers who are well-situated to make use of it right now in their work.
No. 8	When asked for ideas on how to take things learned about FEA on this project and leverage it forward to future projects, described the importance of helping customers to understand how we are using FEA in product development, so we can achieve their buy-in and support. "I think it's just a matter of getting a wider buy-in, instead of just the product development team - getting the customers, getting higher-level assemblies involved, and making sure they understand what decisions are being made from the FEA, and where we would like to use it in the verification and validation process."
No. 11	At the end of the project, when asked how beneficial FEA was for the project overall, replied, "I think it helped the team learn about FEA, and introduce the group as a whole to FEA and how the results can match the model, and therefore the model can help you. But, I'm still not 100 percent sure it actually drove any design decisions, so, in that sense, I'm not sure it helped the design aspect." In other words, the MAIN value of FEA in this case was in terms of the learning process, rather than actual, direct product design impacts. On the other hand, when asked for ideas on how to take things learned about FEA on this project and leverage it forward to future projects, replied, "The only way I could see doing that would be if the design was similar. Maybe you could reutilize the same design because you know it already meets certain specifications, and you already have a model for it. So maybe you could try to tweak that model for whatever the new project is, and come up with a quick answer as to whether or not it will work." So, did not really seem to see any generally-applicable information that could be re-used in the future, but rather focused on the design-specific information.
No. 12	When asked about ways to improve communication about FEA results amongst the members of the product development team, commented on the importance of everyone on the team being familiar with FEA. "I think everybody on the development team would have to know FEA itself, and what its limitations are… how to look to see if a result is suspicious or not, things like that. … I think everybody has to be able to understand how FEA is used, and what its benefits are, and what its limitations are." When asked for ideas on how to take things learned about FEA

Participant	Learning process
	on this project and leverage it forward to future projects, replied, "[If] you know what the inputs are to the design, and you've seen the responses, and in a future project, if it's a similar input, and you're just improving on the design, you have a starting point. … If you were designing something new, but based on something else - you can always do that analysis on the existing one because you know it works right now. … And you can use that as your baseline to start." So, seems to be commenting on using FEA to answer relative questions (i.e., leveraging design similarity), i.e., focused on design-specific information, rather than generally-applicable information that could be re-used in the future.
No. 13	When asked for ideas on how to take things learned about FEA on this project and leverage it forward to future projects, replied very generally, "I guess, generally, like what I just said: using it as a tool to support your engineering, and not necessarily depending on it as your only tool, but more just like one of the tools in your toolbox, and being able to focus your effort."

Participant	Opinions on appropriate use
No. 1	At the beginning of this project, offered several opinions on how FEA ought to be used. In terms of other sources of design knowledge: "You must have a rudimentary understanding of your system and what you're trying to model and simulate, so that you can then make a hopefully informed decision on the results that you get back from your modeling." In terms of team structure and the role of the analyst: "You need to have that capability within your design team or in your project team." In terms of when to use FEA: "FEA… that's a question that when you start a project, should always be asked, and then you look at the scope of the project, really what are you doing, and then make the decision from there." By the end of the project, when asked reiterated some of those same views: "I would not want to see FEA used as the sole means of validating a design. It has its limitations, as all modeling systems do, so you need to be very careful with that. But I think - you know, keeping with kind of my theme all through the interview here - I'm a big proponent of it, and when used properly with analysis and testing, it's a tool that should absolutely be used on all projects."
No. 4	At the beginning of the project, when asked how FEA was most likely to be beneficial for this project, replied, "Probably to help make design decisions, design trade-offs, and early-on type design decisions." At the end, when asked about how they would or would NOT want to see FEA used on future projects, replied, "Without too much insight into other options - I think Jerrod did a good

Participant	Opinions on appropriate use
	job of incorporating it into the design process, so I would probably push for that." So maintained the focus of wanting to see FEA incorporated in the design process and design decision-making.
No. 7	At the beginning of the project, described how they thought FEA should be used to be most beneficial for this project: "I think it's important to get an FEA model set up, and kind of set up early, and then kind of go through this initial round of testing, and see if you can validate any of those models in testing. And then, based on that, we could use it for, you know, a variety of things…" Also emphasized using FEA early: "If we get, basically, trying to get FEA up as we go, and just make sure on these early testing, we get, or we validate at least some part of the model - maybe not necessarily all of it, but an interface between connectors and boards, or something, could be done. And I think the earlier we do that, maybe, the better we could utilize it for other changes later." At the end of the project, when asked about how they would or would NOT want to see FEA used on future projects, replied, "So I think I would continue to want to see it used how it's used right now. I think it's working. … It doesn't seem like it bogs down anyone too much at the moment. We don't have a full-time person working on it that's kind of separated from the group. So I think I like where this is currently going. I'd still like to see the results - you know, if there's changes, can we use this. If we kind of use it how we used it on the first project, I think it could be very useful. So yeah, I would like to see it used like that. I don't have much experience in the, kind of like, large system models that are sometimes built here, so I don't know if I have enough experience to say, 'I *don't* want it to be used like that,' if other people had other inputs. So yeah, I like where it's currently going, and I'm not sure about the 'not.'" So, seems to want the modeling done within the design team, validated early, and used to support design decision-making as needed.
No. 8	At the beginning of the project, when asked how FEA could best be utilized in the design process, simply remarked, "I can't offer any suggestions. I would just say keep doing what they're doing, because it seems to be working." At the end of the project, when asked about ways they would want to see FEA used or NOT used on future projects, stated, "Well, if it's applicable, I would like to see FEA used in a very similar method, where we use it to help make early engineering decisions, um, and also adding the extra piece that I would love to see modeling and simulation more used to prove requirements." So the idea of using FEA to verify requirements is an interesting idea that is in addition to the idea of using it to build early confidence in the design.

Participant	Opinions on appropriate use
No. 11	At the beginning of the project, expressed a desire to see FEA point out design flaws. "I think it will be giving them greater confidence in their design. I'd like to think it could point out flaws in their design, too, but I'm not necessarily sure I saw that in the first design - the first [case study] project. But I'd like to think that's a possibility." At the end of the project, when asked about ways they would want to see FEA used or NOT used on future projects, stated, "I think if we had the time and money, I would suggest using it. I don't know that I would use it any differently than Jerrod has presented using it. It seemed like trying to show us the areas of concern for the mechanical model is what he was doing, and making sure it would pass testing. So I would try to do it the same way he did it." So overall not a really strong opinion about how or how not to use FEA.
No. 12	No data on views/opinions at the beginning of the project. At the end of the project, stated this was a good use of FEA given the size of the design project. "On bigger scale projects it may be a little harder, just because of the complexity. With complexity you add more variability. So I think for something of this size, it was a great use of the tool." Also, when asked about ways they would want to see FEA used or NOT used on future projects, stated, "I think, definitely, um, kind of creating an FEA model in parallel with the design work. Definitely have it done before, like, tests are done to correlate the results… if you have predictions to start with, and you correlate that with how the test is done, and looking to see how close they match, I think is probably the way to go."
No. 13	No data on views/opinions at the beginning of the project. At the end of the project, their interview responses were peppered with a variety of opinions they seemed to be forming on how best to use (or not use) FEA. One idea was not using FEA on its own: "I think, on its own, it would be a little dangerous to depend solely on an FEA approach to engineering. But if it's coupled with some actual testing or some, you know, other physical or kind of actual production engineering approaches, I think it can be very useful." Another was using FEA to support new designs, in order to highlight and draw focus to weak aspects of the design: "If the design is a new design, I think that FEA can definitely be used to kind of focus your engineering effort to specific points of concern, and really strengthen your design as a whole, by kind of tackling those weak points."

Participant	Exemplar of FEA
No. 1	At the beginning of the project and again at the conclusion of the project, harkened back to a past

Participant	Exemplar of FEA
	project in which a strong, iterative coupling between design, FEA, and testing was used to design and field a system. "It goes back to a project I was on quite a number of years ago, where I saw just how much FEA can assist in the design and test effort, and where it actually allowed us to - from looking at the model, expanding the model out, and using engineering judgment - to really being able to answer some questions that we probably could not test to. And yet we still had the confidence that, as long as we didn't push the model too much to the extremes, it was giving us good answers. So, from that… I've learned, over the years, that with the proper use of modeling, you can really expand your capabilities and improve the design." This, in turn, had become a goal for the present project. "I'm hoping on our program here that we'll be able to do that same type of thing as Jerrod develops and improves the models for our boards and our system."
No. 4	At the end of the project, when asked about how they would want to see FEA used or not used on a future project, remarked, "I think… without too much insight into other options - I think Jerrod did a good job of incorporating it into the design process, so I would probably push for that." So, lacking a better example (or any other example), seems loosely attached to the manner in which FEA was used on this project as a basis for how to use it on future projects.
No. 7	At the end of this project (Project 2), referred back to how FEA was used on Project 1. "Going back to Project 1, I know we actually used some of the original model that Jerrod built for Project 1, and we changed some loads on it, basically, and we saw that the response was very similar, and used that as an argument for not having to re-test the design with the slightly different weight. So that's exactly what I would have wanted to see, and that's good… it aided us in our engineering judgment… that such a change was indeed kind of on the trivial side." When asked about how they would want to see FEA used or not used on a future project, remarked, "I think I would continue to want to see it used how it's used right now. I think it's working. It's not… It doesn't seem like it bogs down anyone too much at the moment. We don't have a full-time person working on it that's kind of separated from the group. So I think I like where this is currently going. I'd still like to see the results - you know, if there's changes, can we use this. If we kind of use it how we used it on the first project, I think it could be very useful." So, this participant has latched on to the way FEA was used in Project 1, and likes how it has been used thus far on Project 2, because the stage has been set going forward on Project 2 to use the FEA model for the same types of decisions that came up late on Project 1.
No. 8	At the beginning of this project (Project 2), when asked

Participant	Exemplar of FEA
	about how FEA could best be utilized in the design process, referred back to Project 1 and stated "I can't offer any suggestions. I would just say keep doing what they're doing, because it seems to be working." At the end of this project, when asked about how they would want to see FEA used or not used on a future project, stated, "Well, if it's applicable, I would like to see FEA used in a very similar method, where we use it to help make early engineering decisions, um, and also adding the extra piece that I would love to see modeling and simulation more used to prove requirements." Also remarked that on a future project, "I would definitely bring up my own experiences on this project on reasons why or how it could be beneficial." So the use of FEA on Project 2 seems to have had at least some influence on this person's views of how FEA should be used.
No. 11	At the end of the project, when asked about how they would want to see FEA used or not used on a future project, stated, "I think if we had the time and money, I would suggest using it. I don't know that I would use it any differently than Jerrod has presented using it. It seemed like trying to show us the areas of concern for the mechanical model is what he was doing, and making sure it would pass testing. So I would try to do it the same way he did it." Clearly the manner in which FEA was used on this project had some influence on this participant's idea of how to use FEA on future projects.
No. 12	In the closeout interview, described the use of FEA on this project as follows: "FEA was used to predict the responses first, and then it was correlated with the test data;" and, "I think on this [project], I really saw them go parallel, versus what I normally see, which is that the analysis is done after the design. I think on this one it was really work in parallel, and I think part of that was just because it was the same designer who was doing the analysis." Stated that on future projects, "It's going to be very important that the FEA analyst and the design engineer work very closely together, so that as changes are made in the design, the FEA person can also make those changes. It has to be very well coordinated. Also, it's got to be done in parallel because a lot of times we can't wait for the design to be done and then create an FEA model, because it takes time away from the schedule. So it has to be completely integrated in order to make a real impact." When asked about how they would want to see FEA used or not used on a future project, remarked, "I think, definitely, um, kind of creating an FEA model in parallel with the design work. Definitely have it done before, like, tests are done to correlate the results, because I've seen personally a lot of times where the testing results are used in order to make the model match the testing, but I've seen it done incorrectly in that way." So while this participant never explicitly

Participant	Exemplar of FEA
	stated, 'In the future, FEA should be used the way it was used on this project,' there is a strong alignment between how they describe the use of FEA on this project and their view of how it should be used in the future.
No. 13	At the end of the project, when asked about how they would want to see FEA used or not used on a future project, stated that "I think that having the FEA model was really useful, to be able to kind of nail down where areas of concern might be, so you can focus your engineering effort in those areas, as opposed to, you know, kind of guessing - or making, you know, kind of educated guesses, but - I think it helps to focus your energy, which is… I think that's crucial to getting a good design out in a reasonable amount of time." So no explicit statement that 'In the future, FEA should be used the way it was used on this project.' But a recognition of certain advantages that FEA brought to this project.

Participant	Conceiving of new applications
No. 1	On at least three separate occasions, proposed the use of FEA to form initial estimates for the vibration/shock levels seen by various subcomponents in our assembly and/or for other component groups working on the same overall project. The first suggestion was with regard to the two small rectangular electronics packages that are contained in our assembly. For these components in particular, this was a very insightful suggestion -- in fact, I ended up doing just that and providing the results to that team. The other two suggestions pertain to components that are outside of our assembly. Overall, this seems to suggest an increasing role of FEA in this person's thinking, with at least a reasonably strong grasp of what the FEA models are able to tell us.
No. 4	When discussing with this participant how many DC-to-DC converters the design would need, and the fact that they are also used to help structurally damp the system in vibration/shock environments, this person proposed using FEA to assess how much of an impact removing them from the design would have on vibe/shock performance. On another occasion, discussing some work related to this project in which there is a need to investigate the mechanical integrity of a sealed vessel under conditions of internal pressure. After the team meeting, this participant asked if FEA could be used to answer this question. Had a really good insight on how to deal with some of difficult, non-linear effects in the proposed modeling effort, in order to keep the FEA simple enough and rapid enough to support the product development effort. Involved re-framing the question posed to the FEA so it could be as simple as possible while still providing the answer/confidence needed. On yet another

Participant	Conceiving of new applications
	occasion, after the presentation of the test results compared to FEA results, this participant approached the investigator with more thoughts on the mechanical design in terms of vibration/shock response: Would asymmetric mounting points, or staggered mounting points going up the stack) help prevent the resonances where all boards participate? Would rings to capture the board edges help? It's clear this participant likes thinking about the mechanical design aspects of the project, and that the FEA and test results fuel thinking about how to make the design better.
No. 7	Suggested a possible future use for the FEA vibe/shock models developed for this case study--in the future, when the design is in full production, and questions arise due to problems in the field or during manufacturing, requiring some sort of design change for which there is very limited budget to do the design work and/or any testing--perhaps these FEA models could be used to provide some confidence in a design adjustment.
No. 8	Three interesting suggestions, all reflecting a project planning / system qualification point of view. 1. At the beginning of this project, suggested, can FEA help address late-changing requirements? 2. Also at the beginning, suggested, can enough confidence be gained in FEA techniques that FEA can be used in lieu of some testing on future projects? 3. At the end of the project, discussed the idea, can FEA be used to verify and validate requirements? On that last one, it's not clear if they mean validate that a design meets some requirements (via FEA rather than via experimental testing), or, verify that the requirements for a product are correct, which could involve, e.g., using FEA to model a system and pass requirements on down to sub-components.
No. 11	No data indicating this person proposed any applications of FEA.
No. 12	No data indicating this person proposed any applications of FEA.
No. 13	No data indicating this person proposed any applications of FEA.

Participant	Likely to carry FEA forward
No. 1	At the end of the project, when asked if they would be more likely to be skeptical of using FEA on future projects, an advocate for FEA on future projects, replied, "I am definitely an advocate, I think as long as you start out a project with the idea of using FEA so that you can put that into your schedule and understand that it takes time to get the initial models set up and working and it just gets folded right into the design process. And as long as you have that as part of your thought process - for me, anyway - it's just a natural…

Participant	Likely to carry FEA forward
	something that I think about when I'm talking with my people on scheduling and all that - that's just part of the design process." So clearly (and consistent with the data for this participant), they seem likely to carry the use of FEA forward to future projects.
No. 4	At the end of the project, when asked if they would be more likely to be skeptical of using FEA on future projects, an advocate for FEA on future projects, replied, "I think I'm more of an advocate," but did not elaborate.
No. 7	At the end of the project, when asked if they would be more likely to be skeptical of using FEA on future projects, an advocate for FEA on future projects, replied, "I think I'd be an advocate, in a limited sense, at least - that's what I got from this project. You can do something. With not a mountain of effort, you can get something that's reasonable. I don't know what his total time added up to building this model is, but it didn't seem like it was all he was doing for that period of time. It seemed like he was getting other work done as well. Especially if we can use it in the future, to answer design questions - I think that will actually save time rather than hurt us. It all depends on the project. And it might be… that would be no one's fault if the project goes perfectly, and we don't have to change anything, that's great, I don't know if I would regret building the model at that point. Looking back, you know, hindsight is 20-20. It's like, okay, well, we didn't really need to do it there. But you never know what's coming, and who knows. Maybe it's useful for when these things are in the field for a while, and something comes back, and you have to make a change, but you no longer have the budget for a lot of testing or something like that, because that does happen around here. If those FEA models still exist, and future engineers have access to them, I think that could be something that's useful too. So even if it's not utilized fully on this project, maybe it will be in the future. So I think, overall, yeah, I would be an advocate. If we find some way to, you know, transfer this knowledge, pass it on, make sure that this FEA and this project and how it was constructed kind of stay in sync and people know the assumptions and all that."
No. 8	At the beginning of the project, stated, "In terms of setting up a project, I would say if we have the resources to do FEA analysis, I would definitely recommend it for a similar project in the future, such as project number 2, or other projects not associated with the program we're working on. … I would recommend it moving forward to other programs in a similar situation - to go down this path as we have." At the end of the project, when asked if they would be more likely to be skeptical of using FEA on future projects, an advocate for FEA on future projects, replied, "I would

Participant	Likely to carry FEA forward
	definitely be an advocate… but it would also depend on the makeup of the team and, you know - mostly if the design engineers believe that it would be beneficial. But I would definitely bring up my own experiences on this project on reasons why or how it could be beneficial.” So overall, this participant seems very supportive, thinking about the possibilities, and likely to recommend or suggest FEA on future projects, but ultimately would rely on and defer to the judgment of the engineers more directly responsible for the design work to make that determination.
No. 11	At the end of the project, when asked if they would be more likely to be skeptical of using FEA on future projects, an advocate for FEA on future projects, replied, “I wouldn’t be *more* skeptical [of using FEA]. I think I’d be maybe a hesitant advocate, because I would like to use it, but it would all be based on time and money. … So I would like to use it, and I would like to see it be useful, I just don’t know if our atmosphere is receptive to that. … We’re always going to have to do testing, so if we always have to… I guess it’s good to always have a model too, but if it’s one or the other, we’re always going to have to do the testing, whereas we’re not required to have the model, therefore if money is limited, or time is limited, clearly one is going to win over the other. … While I’m not more skeptical, and I’m a little bit more of a believer, I just don’t know if I could get it to be important in other people’s minds who could control the money.” So overall, this participant seems interested in the possibilities of FEA, but still somewhat skeptical that in a product development world driven largely by schedule and budget, that FEA can truly be elevated from the level of ‘nice to have’ or ‘good to do’ to ‘essential,’ such as prototype testing is.
No. 12	At the end of the project, when asked if they would be more likely to be skeptical of using FEA on future projects, an advocate for FEA on future projects, replied, “I still have mixed feelings about it. It really depends on the designer and the analyst. I think if the analyst and the designer know how to implement FEA correctly, then I would be a huge advocate for it. But it really comes down to trusting the person who is doing it.” So this participant overall seems perfectly open to FEA technology in and of itself, but hesitant in terms of it being used correctly, or with the appropriate attention to detail, or with accurate communication between all the people involved (design engineer, analyst). Unclear, then, if they would be likely to carry its use forward to future projects.
No. 13	At the end of the project, when asked if they would be more likely to be skeptical of using FEA on future projects, an advocate for FEA on future projects, replied, “I think that, based on this project, I’d

Participant	Likely to carry FEA forward
	probably be more likely to be an advocate for using FEA, especially, like I said, if you're working on a new design. And then again, also, if you - I guess this is true of any engineering tool - but if you have someone competent to do the work, um, I think that it can be really useful and can really shorten your design cycle by kind of starting off with something that's pretty well understood." So overall, this person seems open to FEA in the future, and somewhat likely to advocate for its use in the future.

Appendix I: IRB/HSB Protocols and Approvals

Stanford Institutional Review Board (IRB) and Sandia Human Studies Board (HSB) applications and approvals are provided below for reference. The Sandia participant consent form is also included.

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Research Compliance Office

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- See *Does My Project Need IRB Review?*; *Definitions and Regulations*.
- If there is *any question* as to whether your project is *human subject research* you must submit this form to the IRB; *complete all sections then email to IRBCoordinator@lists.stanford.edu*.

Activities that are *clinical investigations* covered under FDA regulations [FDA 21 CFR 50.3(c)] and which involve *human subjects* [21 CFR 50.3(e); 21 CFR 56.102(g)] require IRB review. Do not use this form – submit a protocol application to the IRB at https://eprotocol.stanford.edu/irb.

Protocol Director: **Jerrod Peterson**		Degree: **M.S.**	Title: **Ph.D. candidate**
Dept/Div: **Mechanical Engineering**	Mail Code **n/a**	Ph: **925-294-6197** Fax: **925-294-1539**	E-mail: **jerrodp@stanford.edu**
Alt. Contact: **Sheri Sheppard**		Ph: **650-721-9433** Fax: **650-723-3521**	Degree: **Ph.D.** Title: **Professor** E-mail: **sheppard@stanford.edu**
Project Title: **Integrating the use of finite element analysis (FEA) into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock inputs**			

Purpose of the project – *provide a 3-5 sentence lay description:*

In addition to the quantitative aspect of this research (development and application of FEA modeling techniques for engineering design purposes) there is a qualitative aspect that involves assessing how the use of these techniques impacts the design process and the thinking of the design team members. In order to assess this impact, an initial online survey followed by subsequent one-on-one interviews will be used. The present IRB application covers the initial online survey only, which will collect information on the participants' past exposure to FEA and their views on the benefits and limitations of using FEA as part of a product development effort. The survey will be conducted using Qualtrics web-based software and distributed to approximately 10-12 employees at Sandia National Laboratories (Livermore, CA), where a design project is presently being used as a case study. The purpose of the case study is both to demonstrate the use of the developed FEA modeling techniques, and to investigate how the use of these techniques in a project setting affects the design process.

Note: To clarify, this research belongs to the same overall body of research as that discussed in a previous application submitted to the IRB on 11/4/2011, which per an email received from K. Murphy on 11/12/2011 was determined to not meet Stanford's definition of human subject research. However, this is a distinct portion of the research, serving a different purpose and involving a different group of participants, so I am submitting this separate application.

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Project procedures – *describe all project procedures; include the source of data or specimens and circumstances under which they were/will be collected:*
Each individual will be asked if they are willing to take the online survey, which is estimated to take about 45 minutes to complete. It is anticipated that most participants will complete the survey at Sandia National Laboratories in Livermore, CA, during working hours, at a time that is convienient for them, but the participants may also elect to complete it at home.

All survey results will be compiled for use in the Protocol Director's Ph.D. dissertation research. In the final (i.e., published) format, the survey results will not indicate the names of any particpants (for personnel security reasons) nor the names of any projects they refer to in their responses (for project security reasons). Only the Protocol Director will have access to any information of this nature that is included in the survey results.

The survey questions are listed below. Note that not all participants will be asked every question; the survey contains some logic such that the answers provided to certain questions dictate which questions are asked later on.

1. What is your technical background or degree field?
2. How long have you worked at Sandia (or your current employer)?
3. What is your role on this project?
4. Have you ever seen FEA used on your past projects?
5. Have you ever used FEA software?
6. Have you ever taken a course on FEA?
7. Have FEA results ever influenced your own thinking or activities on a project?
8. Have you ever seen FEA results have an influence on team decision-making?
9. What areas have you seen affected by the use of FEA?
10. How have you seen these areas affected by the use of FEA?
11. Please describe any factors that you think have an effect on the value or usefulness of FEA results.
12. Please describe any ways you have seen the use of FEA either help or hinder a project.
13. Have you ever seen the use of FEA be well-integrated with design activities?
14. Have you ever seen design activities and FEA performed in isolation from each other?
15. Have you ever seen FEA used early on in the design process, before design concepts are developed in full detail and before hardware prototypes exist?
16. What are the advantages and/or disadvantages of integrating design activities and the use of FEA?
17. What are the advantages and/or disadvantages of performing design activities and FEA in isolation from each other?
18. Does the use of FEA tend to lead, keep pace with, or lag design activities and/or team decision-making?
19. In your opinion, how valuable is the use of FEA early on in the design process, and why?
20. Do you ever make (or participate in) decisions that affect the mechanical design of a product?
21. Have you ever seen FEA results presented that did not seem trustworthy or accurate?
22. Have you ever seen FEA results presented that were not explained in a way that was clear and meaningful?
23. For mechanical design issues, what factors most influence your own engineering intuition?
24. What factors have you seen outweigh FEA results in team decision-making?
25. How would describe your own thought process in terms of weighing FEA results against your own engineering intuition?
26. What factors tend to affect your impression of the credibility of FEA results?
27. Please describe any factors that you feel are important for ensuring that FEA results are clear and meaningful for a product design team.
28. Have you ever been involved in deciding whether or not to use FEA as part of a product design or analysis effort?
29. Has the cost of using FEA ever been a factor in deciding whether or not to use it?
30. Has the time required to utilize FEA ever been a factor in deciding whether or not to use it?
31. How have you seen the use of FEA implemented in terms of allocating project resources (such as budget, schedule, personnel, etc.)?
32. How has the cost of using FEA been a factor in determining whether or not to use it?
33. How has the time required to utilize FEA been a factor in determining whether or not to use it?
34. Please describe any thoughts you have on how project planning efforts can/should address the use of FEA.

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---------------- Is the activity RESEARCH? [OHRP] ----------------

Research: A systematic investigation designed to develop or contribute to generalizable knowledge

	Yes	No
Do you consider this project to meet the definition of **research**? If "no", explain why:	☒	☐

---------------- Does this research involve HUMAN SUBJECTS? ----------------

	Yes	No
Does your project include obtaining data or specimens **about a living individual** through intervention or interaction with the individual?............	☐	☒
Does your project involve the use of existing data or specimens?	☐	☒
If "yes"**:**		
• Do the data or specimens contain identifiable private information (i.e. the identity of the subject is or may be readily ascertained or can be associated with the information)?	☐	☐
• Are the data or specimens coded such that a link exists that could allow the data or specimen(s) to be re-identified?............	☐	☐
If "yes", is there agreement prohibiting the PD and their staff access to the key to the code?	☐	☐
• Were the data or specimens originally collected for this project?............	☐	☐
• Were the data or specimens originally collected as part of clinical care?............	☐	☐
• Were the data or specimens originally collected for research purposes under an IRB approved protocol?	☐	☐

---------------- Is the activity CLINICAL INVESTIGATION? [FDA] ----------------

	Yes	No
Does your project include testing the safety and efficacy of a drug or device in a human subject?............	☐	☒
Does your project include an *In Vitro* Diagnostic Device?............	☐	☒

---------------------------- Other Considerations ----------------------------

	Yes	No
Does your project involve human embryonic stem cells (hESC), adult human stem cells, pluripotent cells or somatic nuclear transplantation?	☐	☒
Does your project involve the use of fetal tissue?	☐	☒
Is your project being conducted all or in part at the VA, or with VA resources or personnel?	☐	☒

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	Yes	No
Are you using samples that contain biohazardous/infectious agents? If "yes"**:** • *Refer to the Administrative Panel on Biosafety prior to performing studies*	☐	☒

------------------------------ Federal Funding ----------------------------

	Yes	**No**
Is your project supported by federal funding (e.g., NIH)? If "yes"**:** • *Provide a copy of the federal grant application for this project with this form*	☐	☒

Thank you for your application – the IRB will send you a
Notice of Determination of Human Subject Research
or will contact you if more information is needed.

For IRB use only

Stanford University HRPP	**Notice of Determination of Human Subject Research**	NOT-H3 1/1

From: Kevin W. Murphy, CIP
Phone: (650) 723-5215
Email: kevin.murphy@stanford.edu
Date: December 8, 2011
To: Jerrod Peterson
eProtocol number (if applicable):
Study Title: Integrating the use of finite element analysis (FEA) into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock inputs

The Stanford IRB has made the following determination about the activity described in the above referenced application based on OHRP and FDA regulations and guidance.

☒ THIS PROJECT DOES NOT REQUIRE SUBMISSION TO THE STANFORD IRB, BECAUSE:

☐ **This project does not meet the Federal definition of research.** *"Research is a systematic investigation designed to develop or contribute to generalizable knowledge."*
<Comment>

☒ **This research does not involve human subjects because**:
- ☒ It is not about living individuals
- ☐ You will not be intervening or interacting with study subjects
- ☐ You are not obtaining or receiving individually identifiable private information
- ☐ The data or specimens were collected for purposes other than the current research, the identifiers for the data or specimens have been replaced with a code, and you and your research team are prohibited from obtaining the key to the code.

This is a qualitative analysis of finite element analysis and not about the individuals who are answering the survey.

☐ **Although this project does meet the Federal definition of human subject research**, Stanford is not engaged in human subject research because:
<Comment>
[OHRP Guidance http://www.hhs.gov/ohrp/policy/engage08.html]
Note: *This project is subject to review by* _____

☐ THIS PROJECT IS HUMAN SUBJECT RESEARCH THAT REQUIRES REVIEW BY THE STANFORD IRB.
SUBMIT A NEW ePROTOCOL APPLICATION AS INDICATED:
☐ Medical or ☐ Non-Medical
☐ Exempt - Paragraph ☐ Expedited - Paragraph ☐ Regular
<Comment>

THIS ACTIVITY MAY REQUIRE OTHER APPROVALS.
- ☐ Contact the appropriate committee below before proceeding with your study:
- ☐ VA: Linda Wester at 650-493-500 ext. 65418, linda.wester@va.gov
- ☐ School of Medicine Privacy Officer: Todd Ferris, 650-725-1825, tferris@stanford.edu
- ☐ IACUC: Valerie Fratus, 650-723-4550, valerie.fratus@stanford.edu
- ☐ SCRO: Mario Garcia, 650-724-2866, mario.garcia@stanford.edu
- ☐ APB: Brett Haltiwanger, 650-724-7818, bretth1@stanford.edu
- ☐ Industrial Contracts Office: http://ico.stanford.edu

If you have any questions about this determination or need further guidance on submitting this protocol, please contact me at the above email or telephone number.

NOT03H03 rev 1 10/11 Research Compliance Office

Protocol # 24971 (New)
PD: Jerrod Paul Peterson
Review Type: Exempt
Non-Medical

PROTOCOL
APPLICATION FORM
Human Subjects Research
Stanford University

Print Date: June 6, 2012
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Title : Integrating the use of finite element analysis (FEA) into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock inputs

Approval Period: **Draft**

Protocol Director

Name		**Degree (program/year if student)**		**Title**
Jerrod Paul Peterson		Ph.D. Mechanical Engineering / 3rd year		Ph.D. Candidate, Mechanical Engineering
Dept	**Mail Code**	**Phone**	**Fax**	**E-mail**
Mechanical Engineering		(925) 294-6197		jerrodp@stanford.edu
CITI Training current (within last 2 years)				N

Admin Contact

Name		**Degree (program/year if student)**		**Title**
Jerrod Paul Peterson		Ph.D. Mechanical Engineering / 3rd year		Ph.D. Candidate, Mechanical Engineering
Dept	**Mail Code**	**Phone**	**Fax**	**E-mail**
Mechanical Engineering		(925) 294-6197		jerrodp@stanford.edu
CITI Training current (within last 2 years)				N

Co-Protocol Director

Name		**Degree (program/year if student)**		**Title**
Dept	**Mail Code**	**Phone**	**Fax**	**E-mail**
CITI Training current (within last 2 years)				

Other Contact

Name		**Degree (program/year if student)**		**Title**
Dept	**Mail Code**	**Phone**	**Fax**	**E-mail**
CITI Training current (within last 2 years)				

Faculty Sponsor

Name		**Degree (program/year if student)**		**Title**
Sheri D Sheppard				Professor
Dept	**Mail Code**	**Phone**	**Fax**	**E-mail**
Mechanical Engineering - Design	4021	(650) 721-9433		sheppard@stanford.edu
CITI Training current (within last 2 years)				N

Other Personnel

Title : Integrating the use of finite element analysis (FEA) into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock . . .

Approval Period: **Draft**

Name		Degree (program/year if student)		Title
Helen Lihuei Chen				Soc Sci Res Assoc
Dept	**Mail Code**	**Phone**	**Fax**	**E-mail**
Mechanical Engineering - Design	2055	(650) 924-0228	(650) 725-0192	hlchen@stanford.edu
CITI Training current (within last 2 years)				Y

Name		Degree (program/year if student)		Title
Samantha Ruth Brunhaver				SU Student - Summer
Dept	**Mail Code**	**Phone**	**Fax**	**E-mail**
School of Education	4021			sbozek@stanford.edu
CITI Training current (within last 2 years)				Y

Participant Population(s) Checklist

	Yes/No
• Children (under 18)	N
• Wards (e.g., foster children, incarcerated youth)	N
• Pregnant Women	N
• Impaired Decision-Making Capacity	N
• Cancer Subjects	N
• Laboratory Personnel	N
• Healthy Volunteers	N
• Students	N
• Employees	Y
• Other (i.e., any population that is not specified above)	N

Study Location(s) Checklist

	Yes/No
• Stanford University	Y
• Other (Click ADD to specify details)	Y

Location Name	US/International
Sandia National Laboratories, Livermore, CA	US

General Checklist

Collaborating Institution(s) Generally, when one or more institutions work together **Yes/No**

equally on a research endeavor, it is a collaboration.

- Are there any collaborating institutions? N

Payment or Reimbursement **Yes/No**

- Subjects will be paid or reimbursed for participation? See payment considerations. N

Funding **Yes/No**

- Training Grant? N
- Federally Sponsored Grant? N

Funding

NONE

Funding - Grants/Contracts

Funding - Fellowships

Gift Funding

Dept. Funding

Other Funding

Resources :

a) Qualified staff

State your and/or your study staff's qualifications to conduct this study.

My qualifications:
- M.S., Mechanical Engineering, Oregon State Univ. (2004)
- Ph.D. Candidate, Mechanical Engineering, Stanford Univ. (expected 2013)
- I am a full time employee of Sandia National Laboratories (2003-present)
- I am currently participating in Sandia's University Part-Time program, under which Sandia covers the cost of tuition and fees at Stanford while I pursue a Ph.D. in mechanical engineering with a focus on the research area described by the title of this Protocol.

Qualifications of others assisting with the research:
- Dr. Sheri Sheppard (Faculty Sponsor and interviewer): Professor, Mechanical Engineering, Stanford University.
- Samantha Brunhaver (interviewer): Ph.D. Candidate, Mechanical Engineering, Stanford University. Involved in past studies in the College of Engineering involving Human Subjects Research. Experienced interviewer.
- Dr. Helen Chen (interviewer): Research, Center for Design Research, Stanford University. Involved in past studies in the College of Engineering involving Human Subjects Research. Experienced interviewer.

Note: Sheri, Samantha, and Helen have agreed to conduct the interviews, but are doing so on a voluntary basis and are not being paid to participate in the research project.

b) Training

Describe the training you have received regarding the research-related duties and functions of this protocol. Also, describe the training received by study staff assisting you with the research.

My training:
- I am currently in the process of completing the applicable CITI training required by Stanford for non-medical human subjects research in the College of Engineering.

Training of others assisting with the research:
- Samantha and Helen have received and are current on the required CITI training.
- I believe Sheri has received the CITI training in the past, but in any case it appears her training is out-of-date, so she may need to take the refresher course prior to conducting interviews.

c) Facilities

Describe where the study will take place, including where data will be collected and where it will be analyzed.

The study will take place at Sandia National Laboratories in Livermore, California.

d) Time

How much time will be needed to conduct and complete the research?

Each inidividual interview is expected to require about 45 - 60 minutes.

e) Participant access

Will you have access to a population that will allow recruitment of the required number of participants?

Yes.

f) Access to resources

Will you have access to psychological resources that participants might need as a consequence of participating in the research? If yes, describe these resources. Enter N/A if the need for psychological resources is not anticipated.

N/A

Title : Integrating the use of finite element analysis (FEA) into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock . . .

Approval Period: **Draft**

Exempt Form

Federal regulations state that certain research is exempt from review. However, under Stanford's Policy for the Protection of Human Subjects, a research protocol proposing the use of human subjects must be submitted to the IRB to determine if it qualifies for exempt status. All protocols must meet Stanford HRPP ethical standards governing the conduct of research.

Exempt status WILL NOT be granted when research:

- involves prisoners as participants
- involves children in category 2 below EXCEPT for the observation of public behavior when the researcher does not participate in the activity being observed
- involves significant physical invasions or intrusions upon the privacy of the participants

Review your exempt category selection(s) below. Make changes as applicable.

1. N **Research conducted in established or commonly accepted educational settings, involving normal educational practices, such as:**
  i) research on regular and special education instructional strategies; or
  ii) research on the effectiveness of or the comparison among instructional techniques, curricula, or classroom management methods.

2. Y **Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior UNLESS:**
  i) information obtained is recorded, such that human subjects can be identified directly or through identifiers linked to the subjects;
  AND
  ii) any disclosure of the human subjects' responses outside the research could reasonably place subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

3. N **Research involving educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures, or observation of public behavior that is NOT exempt under 2 above, if:**
  i) the human subjects are elected or appointed public officials or candidates for public office; or
  ii) federal statute(s) require(s) without exception that the confidentiality of the personally identifiable information will be maintained throughout the research and thereafter.

4. N **Research, involving the collection or study of existing data, documents, or records, if these sources are publicly available OR if the information is recorded by the investigator in such a manner that subjects cannot be identified, directly or through identifiers linked to the subjects.**

Yes/No

N Are the data, documents, or records pre-existing (on the shelf as of today)? If no, you do NOT qualify for Exempt Category 4.

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Note: Information must be recorded by the investigator in such a manner that subjects cannot be identified directly or through identifiers linked to the subjects.

Provide the dates these data were collected (use mm/dd/yyyy to mm/dd/yyyy). Indicate where the data came from (e.g., public records, data collected for a non-research purpose, previous study records, teacher's personal records, registrar's office).

5. N **Research and demonstration projects which are conducted by or subject to the approval of Department or Agency heads, and which are designed to study, evaluate, or otherwise examine:**
- i) public benefit or service programs;
- ii) procedures for obtaining benefits or services under those programs;
- iii) possible changes in or alternatives to those programs or procedures; or
- iv) possible changes in methods or levels of payment for benefits or services under those programs.

6. N **Taste and food quality evaluation and consumer acceptance studies, (i) if wholesome foods without additives are consumed or (ii) if a food is consumed that contains a food ingredient at or below the level and for a use found to be safe, or agricultural chemical or environmental contaminant at or below the level found to be safe, by the Food and Drug Administration or approved by the Environmental Protection Agency or the Food Safety and Inspection Service of the U.S. Department of Agriculture.**

1. Purpose

a) **In 3-5 sentences, state the purpose of the study in lay language.**

In addition to the quantitative aspect of this research (development and application of FEA modeling techniques for engineering design purposes) there is a qualitative aspect that involves assessing how the use of these techniques impacts the design process and the thinking of the design team members. In order to assess this impact, an initial online survey (already conducted) followed by two rounds of one-on-one interviews (covered by this protocol) with the design team members will be used. The interviews have been designed to follow-up on the participants' survey responses, and to ask about their participation and experiences on two recent design projects at Sandia National Laboratories that are being used as case study design projects. The purpose of the case studies is both to demonstrate the use of the developed FEA modeling techniques, and to investigate how the use of these techniques in a project setting affects the design process and design team members.

Note: To clarify, this research belongs to the same overall body of research as that discussed in two previous applications submitted to the IRB on 11/4/2011 and 11/29/2011, which per emails from K. Murphy received on 11/12/2011 and 12/8/2011, respectively, were determined to not meet Stanford's definition of human subject research.

b) **State what you hope to learn from the study and assess the importance of this new knowledge.**

The fundamental question driving the portion of the research covered by this protocol is: how does the use of FEA in the product development process impact the design team members? It is understood that the use of FEA, from a purely technical perspective, poses many advantages and holds much potential for improving engineered products and our understanding of them. But achieving an optimal implementation of the use of FEA in an actual product development effort, when resource constraints are a factor and a variety of approaches may exist for developing and qualifying a product, has proven difficult in the past. It is essential to develop a deeper understanding of how design team members from a variety of technical

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backgrounds view and percieve the benefits and limitations of FEA in the context of real product development efforts. This understanding, in turn, can be used to help improve the use of FEA and properly scope its role in the product design and development process. To this end, the two case study design projects at Sandia National Laboratories are being used as an opportunity to ask the following research questions:

- What evidence do design team members show that FEA is becoming part of their thinking?
- What examples (if any) do they identify of using FEA to help answer design questions or to better understand their designs?
- To what extent do they view FEA as part of a legitimate engineering approach?
- How do they view the feasibility of using FEA within the resource limitations of the project (schedule, budget, personnel)?
- In what ways do the impacts extend to team members with other technical backgrounds?
- In what ways do team members who are 'learners' (novices) with regard to FEA demonstrate an increased awareness of its abilities, limitations, and nuances?
- In what ways do team members who are 'experienced' (relative experts) with regard to FEA demonstrate a shift or refinement in their thoughts on the appropriate or optimal use of FEA?

2. Study Procedures

a) **Describe ALL the procedures human participants will undergo. Are the research procedures the least risky that can be performed consistent with sound research design?**

Each individual on the 9-member design team will be asked if they are willing to participate in the interviews, which will be conducted online using videoconferencing software. The interviewer will be either Dr. Sheri Sheppard (Professor of mechanical engineering), Samantha Brunhaver (Ph.D. candidate in mechanical engineering), or Dr. Helen Chen (Center for Design Research), all of Stanford University. Approximately 3 interviews will be handled by each interviewer. The interviewees will be located at Sandia National Laboratories in Livermore, California (the site where the case study design projects are occurring). The interviewers will be located at Stanford University. Interviews will be conducted during business hours, at a time that is convenient for each participant, and are estimated to require 45-60 minutes to complete. The interviews will follow a guided interview protocol generated by the Protocol Director. Some slight customization of the questions will be included, based on a coding of the participants' responses in the online survey.

It is believed that that these interview procedures present minimal risk to the interview participants.

b) **State if audio or video recording will occur. Describe how the recordings will be used, e.g., shown at scientific meetings, used for transcription. Describe the final disposition of the recordings, e.g., erased, stored.**

The interviews will be recorded in both audio and video format. The interviewees will be asked if they consent to have audio and video recorded during the interviews. The only purpose of the recordings is to generate interview transcripts.

All interview transcripts/results will be reviewed and compiled for use in the Protocol Director's Ph.D. dissertation research. In the final (i.e., published) format, the interview transcripts/results will not indicate the names of any particpants (for personnel security reasons) nor the names of any projects they refer to in their responses (for project security reasons). Only the Protocol Director and the interviewers will have access to the first names of the interviewees.

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The recordings will be deleted/erased upon generation of the interview transcripts.

c) **DECEPTION: Will participants be fully informed about the purpose of the study? If no: provide a rationale for deception.**

Yes.

3. Reserved for future use

4. Participant Population

a) **How many participants do you expect to enroll? What type of participants will you enroll (e.g., high school students, teachers, government officials)?**

It is expected that 9 members of the design team will participate in these two rounds of interviews. All are employees of Sandia National Laboratories, with the exception of one, who is an employee of Honewell Federal Manufacturing & Technologies Kansas City Plant and a colleague/associate of the design team at Sandia.

b) **What are the age range, gender, and racial or ethnic background of the participant population being targeted?**

Age range: approximately 26 to 55.
Genders: male (7/9) and female (2/9).
Ethnic background: varies, but mostly Caucasian. (more information can be provided upon request.)

c) **If applicable, explain why potentially vulnerable participants are needed (e.g., children, pregnant women, students, economically or educationally disadvantaged, homeless, people with impaired decision making capacity).**

N/A

d) **Reserved for future use**

e) **Will any participants be your students, laboratory personnel and/or employees? See Stanford University policy at http://www.stanford.edu/dept/DoR/rph/7-5.html).**

Yes. See (a) above.

f) **How will you recruit participants (e.g., ads, classroom recruitment, word of mouth, letters mailed home, email)? Attach recruitment materials in the Attachments section. YOU MAY NOT CONTACT POTENTIAL PARTICIPANTS PRIOR TO IRB NOTICE OF EXEMPTION.**

The potential participants are colleagues at my place of employment. I work with all of them regularly: some very frequently (every day), others less frequently (once every several weeks, on average). Contact would be in person, where feasible, but could be via email or phone, if necessary.

g) **PAYMENT or REIMBURSEMENT. Will participants be paid or reimbursed for participation? If yes, how much, and explain why proposed payments/reimbursements are reasonable. Explain how payment will be prorated, if there is more than one study session. See payment considerations.**

No.

h) **Explain what costs will be incurred by the participant. If none, enter 'none'.**

None.

i) What is the total time that each participant will spend in the entire study (e.g., 20 minutes, 2 hours, 3 days)?

Each interview is expected to take about 45-60 minutes. At most, participants would be involved in two such interviews. The first round of interviews will be conducted on/around July 2012. The second round of interviews will be conducted on/around January-February 2013.

5. Risks

a) Describe any reasonably anticipated potential risks(s), including risk(s) to physical, psychological, political, economic or social well-being. If risks are not reasonably anticipated, enter 'none'.

None.

b) If you are conducting research outside the US (international research), describe qualifications/ preparations that enable you to both estimate and minimize risks to participants. Then complete the International Research Form and attach it in the Attachments section. If not applicable, enter N/A.

c) Reserved for future use

d) Children's Findings (OHRP)

Select the category below that best describes your research, if children are involved.

Rationale:

6. Benefits

a) **Describe the potential benefit(s) to be gained by the participants and/or by society as a result of this study. If none, enter 'none.'**

Participants: The only benefit, if it could be considered one, is the satisfaction of being asked to think critically about the benefits and limitations of an engineering tool (FEA) and then having an opportunity to voice their thoughts.

Society: The benefits, if any, would be indirect, such as improved engineering practices and efficiency within a Department of Energy National Laboratory and/or extension of this understanding to the private sector.

7. Privacy and Confidentiality

Privacy

Privacy refers to the environment in which data are collected from participants (e.g., interviewing participants individually in a place where personal responses will not be seen or overheard).

a) Explain where the research takes place (e.g., in a lab, online, at school). Describe how you will

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Approval Period: Draft

maintain privacy in this setting.

The interviews will take place at work (Sandia National Laboratories in Livermore, California), in an office which is fully closed off from adjacent work areas.

Confidentiality

Confidentiality refers to your agreement with the participant about how the participant's identifiable personal information (i.e., identifiable data) will be handled, managed, stored, and disseminated.

b) What identifiable data will you obtain from participants? Enter 'none' if identifiable data will not be obtained. Discuss how you will protect the participants' identity, if applicable.

I work with the study participants and as such know some basic information (such as full names, cities they live in, etc.). For the purpose of the interviews, the 3 interviewers (Sheri, Sam, and Helen) simply need to know the first names of the participants. For the actual published interview transcripts/results used in my Ph.D. dissertation, I can use pseudonyms for their first names, which is easy to do and a best-practice anyway, given the nature of where we work (a Department of Energy National Laboratory).

8. Potential Conflict of Interest

a) Does anyone who:

* recruits, selects, consents, or treats participants
* plans to analyze data
* plans to serve as an author on any papers originating from this research
* is an immediate family member (spouse, dependent child as defined by IRS, domestic partner of any of the above)

N i) have consulting arrangements, responsibilities or equity holdings in the Sponsoring company, vendor(s), provider(s) of goods, or subcontractor(s)?
N ii) have a financial relationship with the Sponsoring company, vendor(s), provider(s) of goods, or subcontractor(s) including the receipt of honoraria, income, or stock/stock options as payment?
N iii) serve as a member of an advisory board with the Sponsoring company, vendor(s), provider(s) of goods, or subcontractor(s)?
N iv) receive any gift funds from the Sponsoring company, vendor(s), provider(s) of goods, or subcontractor(s)?
N v) have an ownership or royalty interest in any intellectual property utilized in this protocol?

b) N To your knowledge, does anyone in a supervisory role to the Protocol Director have a conflict of interest related to this study?

c) N To your knowledge, has Stanford University licensed to a company any intellectual property utilized in this protocol?

If one or more of the above relationships exist, include a statement in the consent form to disclose this relationship, i.e., a paid consultant, a paid member of the Scientific Advisory Board, has stock or stock options or receives payment for lectures given on behalf of the sponsor. The consent form should disclose what institution(s) or companies are involved in the study through funding, cooperative research, or by providing study drugs or equipment.

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Approval Period: **Draft**

If you answer yes to any of the questions above, you must file a Conflict of Interest (CoI) disclosure. See http://rph.stanford.edu/4-1.html for more information. Contact the Barbara Flynn at (650) 723-7226, or bflynn@stanford.edu.

9. Participant Information

If you are using a document (e.g., information sheet, oral script, consent, assent, or other document) that discusses the participant's involvement in your research, attach under "Participant Information" by clicking on the ADD button below and then selecting the appropriate option in the drop-down menu.

• Participant Information

a) Describe the process you will use to inform participants about your study. Include the following: Who will obtain consent? When and how will this be done?

I will meet with each participant individually and describe the research (most of them are already partially familiar with it, since they are my colleagues and they know I am attending Stanford). I will ask them if they would be interested/willing to participate in the interviews. I will verbally summarize the protocol so they have a reasonable idea of what to expect and can make an informed decision about participating. I will describe to them the overall research questions I aim to answer (again, many are already familiar with my research) and how/why their participation would be useful and how the interview results/transcripts will be used. I will answer any clarifying questions they have. If they wish to see a copy of the protocol that will be used to guide the interviews, I will provide that to them.

10. Reserved for future use

11. Attachments

Attachment Name	Attached Date	Attached By	Submitted Date
FEA Interview Guide	06/06/2012	jerrodp	

Obligations

The Protocol Director agrees to:

- Adhere to principles of sound scientific research designed to yield valid results
- Conduct the study according to the protocol approved by the IRB
- Be appropriately qualified to conduct the research and be trained in Human Research protection ethical principles, regulations, policies and procedures
- Ensure all research personnel are adequately trained and supervised
- Ensure that the rights and welfare of participants are protected, including privacy and confidentiality of data
- Disclose to the appropriate departments any potential conflict of interest
- Report promptly any new information, modification, or unanticipated problems that raise risks to participants or others
- Apply relevant professional standards.

Any change in the research protocol must be re-submitted to the IRB for review to re-certify exemption. Any complications in subjects or evidence of increase in the original estimate of risk should be reported at once to the IRB before continuing with the project. The investigators must inform the participants of any significant new knowledge obtained during the course of the research.

All data must be retained for a minimum of three years past the completion of the research. Additional requirements may be imposed by your funding agency, your department, or other entities. (Policy on Retention of and Access to Research Data, Research Policy Handbook, http://www.stanford.edu/dept/DoR/rph/2-10.html)

Y The Protocol Director has read, and agrees to abide by, the above obligations.

STANFORD UNIVERSITY

Stanford, CA 94305 [Mail Code 5579]

Penelope D Eckert, Ph.D. (650) 723-2480
CHAIR, PANEL ON NON-MEDICAL HUMAN SUBJECTS (650) 725-8013

Notice Of Exempt Review

Date: June 11, 2012

To: Jerrod Paul Peterson, Ph.D. Mechanical Engineering / 3rd year, Mechanical Engineering
Sheri D Sheppard, Helen Lihuei Chen, Samantha Ruth Brunhaver

From: Penelope D Eckert, Ph.D., Administrative Panel on Human Subjects in Medical Research

Protocol Integrating the use of finite element analysis (FEA) into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock inputs

Protocol ID: 24971 **IRB Number:** 349 (Panel: 2)

The IRB reviewed your research protocol on June 11, 2012 and determined that the only involvement of human subjects in the research activities will be in one or more of the categories that are exempt from the regulations at 45 CFR 46 or 21 CFR 56. If this protocol is used in conjunction with any other human use it must be re-reviewed. The IRB requests prompt notification of any complications or incidents of noncompliance which may occur during any human use procedure.

Please remember that all data, including all signed consent form documents, must be retained for a minimum of three years past the completion of this research. Additional requirements may be imposed by your funding agency, your department, or other entities. (See Policy on Retention of and Access to Research at http://.stanford.edu/dept/DoR/rph/2-10.html)

Penelope D Eckert, Ph.D., Chair

Review Type: EXEMPT - NEW
Funding: None
Exempt Under Category: 2
Assurance Number: FWA00000935 (SU)

HSB-102 (12/20/11)

Sandia National Laboratories

Human Studies Board

Application for HSB Review

of research involving human subjects

Notes: - *All questions must be answered before the HSB can complete its review.*
- *Check the HSB Forms & Template page to ensure this is the current version of this form.*

---

1. Study Information

a. Is this study **classified?** Yes ☐ If yes, **STOP** & contact the HSB Office
No ☒ Partially, but HSB review can be unclassified ☐

b. **Project Title** Integrating the use of finite element analysis (FEA) into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock inputs

c. Tracking Number SNL______ (*provided by HSB*)

d. **Sponsor** (funding source) Sandia University Part-Time Program____________________

e. **Is research funded?** Yes ☒ No ☐ in process ☐ Approximate amount 0.5 FTE, 40 mo.

f. **Principal Investigator** name Jerrod P. Peterson______________________

Phone: 925-294-6197 Email: jppeter@sandia.gov Org: 08135_____

Mail Stop: 9102 *or* Institution if not SNL ___________________________________

PI signature ____ Date signed __________

Line Director Approval

My signature below attests that I:

- concur that this research needs to involve human subjects, data, or specimens
- have reviewed and approve this proposed work for scientific merit
- acknowledge that the PI is qualified and the right researcher to conduct this study

____ ________________
Printed Name Center Number

____ ________________
Signature Date signed

HSB application page 1 of 13

HSB-102 (12/20/11) Sandia National Laboratories

Questions? *See "Why are they asking that?" (HSB-102 why), or call the HSB office at 845-9171.*

g. Has the PI/co-PI:

- ever received an "FDA Warning Letter"? Yes ☐ No ☒
- ever had any research suspended and/or terminated by an IRB? Yes ☐ No ☒
- ever been disciplined by a medical organization or licensing authority? Yes ☐ No ☒

h. **Research Team**

- List all researchers who will interact with subjects or their data *(add rows as needed)*
- Indicate the Point of Contact if other than the PI

Name	Org	CITI completion date
Jerrod Peterson	**08135**	**6/8/2012**
Sheri Sheppard	**Stanford**	**5/16/2012**
Samantha (Bozek) Brunhaver	**Stanford**	**(Samantha's training is up-to-date)**
Helen Chen	**Stanford**	**(Helen's training is up-to-date)**

i. What is the role of each researcher? Jerrod = P.I.; Sheri, Sam, and Helen = interviewers

j. Will this research be conducted at SNL? Yes ☒ No ☐

If yes, indicate Tech Area & building: SNL/CA, Building 910

If no, indicate all sites where data collection will occur: (Note: data collection will be via online interviews, with the interviewees located at SNL/CA and the interviewers located at Stanford University in Palo Alto, CA.)

k. Are institutions other than Sandia involved in this study? Yes ☒ No ☐

If yes, list all institutions, describe the role of each, and identify the lead site

The principal investigator is presently attending Stanford University under Sandia's University Part-Time Program, and this research is in support of his Ph.D. dissertation. Three researchers at Stanford University will be assisting with the online interviews. That is the extent of Stanford's involvement in this project. Sandia is the lead site and is funding the PI's time on the research project.

Are other IRB approvals required? Yes ☒ No ☐ Don't know ☐ N/A ☐

2. Research Summary

Note: *Answer each question fully; a reference to the protocol is not sufficient.*

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a. **Purpose** – What is the purpose of this research? In addition to the quantitative aspect of this research (development and application of FEA modeling techniques for engineering design purposes), there is a qualitative aspect that involves assessing how the use of these techniques impacts the design process and the thinking of the design team members. In order to assess this impact, two rounds of one-on-one interviews with the design team members will be used. These interviews have been designed to ask the interviewees about their participation and experiences on two recent design projects here at Sandia that are being used as case study design projects in the PI's dissertation research. The purpose of the case studies is both to demonstrate the use of the developed FEA modeling techniques, and to investigate how the use of these techniques in a project setting affects the design process and the design team members.

b. **Why are human subjects necessary** for this study? The research question itself inherently involves human subjects: the idea is to assess the extent and nature of the impact of using FEA early in the design process on the design team members. The team members themselves represent a variety of technical backgrounds and ranges of experience with FEA.

c. **Background** -- Describe the relationship of this proposed study to previous investigations in the field, including citations. Address the scientific rationale and identify specific gaps the research is intended to fill. It is understood that the use of FEA, from a purely technical perspective, poses many advantages and holds much potential for improving engineered products and our understanding of them, especially when used early in the design process during the conceptual design phase (1). But achieving an optimal implementation of the use of FEA in an actual product development effort, when resource constraints are a factor and a variety of approaches may exist for developing and qualifying a product, has proven difficult in the past (2). It is essential to develop a deeper understanding of how design team members from a variety of technical backgrounds view and perceive the benefits and limitations of FEA in the context of real product development efforts. This understanding, in turn, can be used to help improve the use of FEA and properly scope its role in the product design and development process. __

(1) Burman, A. et al, 1994, On a concept for a finite element based design tool, ASME Pressure Vessels and Piping Division, vol. 274, p 103-112.

(2) Schelkle, E. et al., 2001, Virtual vehicle development in the concept state – current status of CAE and outlook on the future, 3rd MSC Worldwide Aerospace Conference & Technology Showcase, Sep. 24-26, 2001, Toulouse, France.

d. **Hypothesis** -- Indicate the scientific question you hope to answer or describe the goals of the study. The fundamental question driving the portion of this research that involves human subjects is: how does the use of FEA in the product development process impact the design team members? To this end, the two case study design projects here at Sandia are being used as an opportunity to investigate and reflect on the following research questions:

(i) What evidence do design team members show that FEA is becoming part of their thinking?

(ii) What examples (if any) do they identify of using FEA to help answer design questions or to better understand their designs?

(iii) To what extent do they view FEA as part of a legitimate engineering approach?

(iv) How do they view the feasibility of using FEA within the resource limitations of the project (schedule, budget, personnel)?

(v) In what ways do the impacts extend to team members with other technical backgrounds?

(vi) In what ways do team members who are who are 'learners' (novices) with regard to FEA demonstrate an increased awareness of its abilities, limitations, and nuances?
(vii) In what ways do team members who are 'experienced' (relative experts) with regard to FEA demonstrate a shift or refinement in their thoughts on the appropriate or optimal use of FEA?

e. **Study Design & Methodology**

(1) What is the experimental design and how is the study being conducted? Two design projects at Sandia are being used as case studies. The purpose of the case studies is two-fold: (1) to demonstrate the use of the developed FEA modeling techniques, and (2) to investigate how the use of these techniques in a project setting affects the design process and the design team members. In order to assess this impact, two rounds of one-on-one interviews with the design team members will be used. These interviews have been designed to ask the interviewees about their participation and experiences on the two case study design projects. The first round of interviews will be used near the conclusion of the first project, and the second round of interviews will be used near the end of the second project.

(2) List all information to be collected from subjects: Please see the attached guided interview protocol which will be used to interview the study participants.

(3) If not already covered in (1) or (2) above, describe exactly what participation in this study will entail for subjects. Participants will be asked if they are interested/willing to participate in two interviews, each lasting about 45-60 minutes. The interviews will be conducted online using Microsoft Lync software, during working hours, at a time that is convenient for the study participants, who will be located at Sandia National Laboratories in Livermore, California. The interviewers will be researchers at Stanford University in Palo Alto, California. The interviews will be conducted using the guided interview protocol that has been submitted along with this form.

(4) Will any **biological specimens** be obtained? Yes ☐ No ☒
If yes, describe what specimens. ________________

(5) Will the data in this study come from a **data set**? Yes ☐ No ☒
If yes, describe the data set. ________________

Be sure to include:
- structure of the data set
- source of the data set
- whether the data is de-identified
- who de-identified the data (if known)

(6) Will data or specimens be sent to another facility? Yes ☐ No ☐ N/A ☒
If yes, identify the facility and attach a copy of the data/specimen transfer agreement.
____

(7) Will data or specimens be stored for undetermined **future use** such as genetic studies?
Yes ☐ No ☐ N/A ☒
If yes, describe. ________________

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Is permission for storage re-contact and future use addressed in consent form?
Yes ☐ No ☐ N/A ☒

Do you plan to re-contact subjects after this study? Yes ☐ No ☒

f. **Timeline** -- Provide a timeline for the study that indicates how long it will take from subject recruitment to completion of data analysis. Subject recruitment would begin immediately following approval by the HSB (e.g., approximately July 2012). Data collection will occur in two phases (more detail provided below) between approximately July/August 2012 to January/February 2013. Analysis of the data collected will be ongoing during that timeframe, and will continue on during the first half of calendar year 2013. Analysis, write-up, and presentation of the data is expected to culminate in June 2013 with the submission of the PI's Ph.D. dissertation to Stanford University.

Also, indicate the overall time commitment for subjects. For more than one engagement, specify the number of visits and the expected duration of each visit. If this work will include more than one phase, indicate how many and approximate dates for each. Data collection will occur in two rounds of interviews with the design team members. The first round of interviews would likely be conducted in the July-August 2012 timeframe, and the second round of interviews would likely be conducted in the January-February 2012 timeframe. Each interview is expected to take about 45-60 minutes to complete, so the total time commitment by each of the participants is maximum 2 hours over the course of the investigation.

3. Scientific Merit

a. Is this research scientifically important enough to justify the potential risks to human subjects?
Yes ☒ No ☐

b. Are there other ways the information could be gotten with less risk? Yes ☒ No ☐

c. If so, how superior is the method being proposed here and how much greater is the risk? Similar information could be collected from the design team members using other methods, e.g., written or online surveys, which might be more comfortable for any participants who are shy or otherwise uncomfortable in an interview setting. However, interviews will provide a better opportunity for participants to articulate their answers with minimal time commitment on their part, and to ensure that those answers are correctly understood (e.g., through the use of clarifying questions). It is believed that any additional 'risk' (if any) posed by the use of interviews is extremely minimal, and is nothing more than that faced by members of the technical staff at Sandia National Laboratories in the routine performance of their job duties as members of Product Realization Teams.

4. Subject Pool

a. **Describe the subject pool** and list all **inclusion criteria**. Indicate **why** this group is **appropriate**

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b. List all exclusion criteria and provide justification for any that are not obvious.

c. Does this study involve any **vulnerable populations**? *Check all that apply*:

- ☐ Minors (under 18 years old)
- ☐ Fetuses/Fetal Tissue
- ☐ Pregnant women
- ☐ Prisoners or Other incarcerated persons
- ☐ Persons unable to give valid informed consent due to physical or mental condition

☒ No vulnerable populations

NOTE: Pregnant women will not be specifically recruited or excluded, since their participation in this minimal risk study poses no risk to them or their unborn fetus.

d. State the **target number of subjects** and explain why this number is appropriate for this study. The target number of subjects will be approximately 9 design team members. This is appropriate because it is (1) a feasible number of interviews to conduct, (2) results in a minimal amount of participant (i.e., employee) time being devoted to the interviews, (3) it should yield sufficient data for determining if the use of FEA over the course of the two case-study design projects has any effect on the thinking of the design team members,

e. **Recruitment --** Describe the subject recruitment strategy you will use (for each group of subjects, if applicable). Include any compensation subjects may receive and what, if any, conditions attach to that compensation. Indicate how potential subjects will be identified and how initial contact or notification will be made. I would approach each target subject in person (or over the phone/email if travel schedules caused an issue), update them on my research (each of them is already aware that I am pursuing a PhD and somewhat aware of my research), describe the research questions I would like to investigate using data collected from interviews, and ask if they would be interested/willing to participate in the interviews. The subjects will not receive any compensation.

f. **Selection --** Describe how subjects will be selected, and what you will do if you have too few or too many potential subjects. Potential subjects will be selected based on the criteria described above (4d) which is a pool of approximately 9 subjects. I will include up to all 9 of them in the study if they are all willing/able to participate. If only 4 or fewer are willing to participate, I will have to consider some other means of obtaining data for these research questions, but I do not anticipate this situation will arise. I think it is highly likely the majority of the potential subjects will be willing to participate.

g. List any **costs to subjects**. No costs will be incurred by the subjects.

h. Does the subject pool include **co-workers from within your center**? Yes ☒ No ☐ N/A ☐
If yes, provide justification for recruiting fellow workers. About half of the design team members (5 of the 9) are from my Center, while just under half (4 of the 9) are from other Centers. The entire research method relies on the fact that I am embedded, so to speak, in the design team. I am an integral part of the design team and responsible for developing the FEA models (among several other responsibilities). As such, I am able to spend significant amounts of time discussing the design projects and constraints with other members of the team, planning and allocating for necessary project resources, and weighing various design options. This gives me a first-hand view of how the team as a whole and the individual team members assimilate the information obtained via the use of FEA into their design thinking and decision making. In order to maximize the objectivity and validity of the data, I plan to have 3 fellow researchers at Stanford University conduct the interviews. I believe this will give the participants the best opportunity to think critically and speak freely about their thoughts and experiences on the case study design projects, and will minimize the potential for any coercion (since I am conducting the research, but am also on the design team with them and am a colleague).

5. Risks

a. Describe all potential risks. As appropriate, include physical, psychological, social, economic, or legal, as well as any that might arise due to a breach of confidentiality. Indicate both their seriousness and likelihood. If there are no benefits to subjects, indicate that. It would be a moderately serious risk to participants to widely disseminate their names, the fact that they work at Sandia National Laboratories, and/or the details of the projects that the case studies are focusing on. However, mitigation strategies will be put in place to deal with this risk (see below), rendering the likelihood of these risks/occurrences extremely low.

b. Does this study involve exposure to **ionizing radiation** (x-rays, radionuclides, CT Scans)?
Yes ☐ No ☒

c. Does this study involve exposure to **non-ionizing radiation** (MRI, ultraviolet, laser, ultrasound)?
Yes ☐ No ☒

d. Will subjects be exposed to chemicals, pharmaceuticals, or other physical agents?
Yes ☐ No ☒

e. Could this work be considered controversial (to subjects or to Sandia)?
Yes ☐ No ☒ If yes, explain. ___________________________________

Risk Mitigation

f. Describe **procedures** for protecting against or minimizing likelihood of identified risks. If the research design creates potential risks, describe any other methods that were considered and why they were rejected. In the final (published) form of the case-study write-up, pseudonyms will be used for all participants. The first names (and only their first names) will be given to the three researchers at Stanford who will be conducting the interviews. Also, the name/details of the program that the case-study participants are working will not be included in the case-study write-up nor given to the interviewers from Stanford. This mitigates against risks to the human subjects, as well as against overall risks to Sandia in terms of security issues. (Corporate Review and Approval will also be used and is the formal means for ensuring that risks are adequately addressed from a classification perspective.)

g. If any vulnerable populations (see p. 4) are included in this study, state what additional protective measures to be taken with those subjects. N/A ☒ ______________________________

6. Benefits

a. Describe the benefits that subjects might reasonably expect from participating in this study. Also, describe any potential benefits to Sandia and to society or some subset. Note that payment to subjects is not a benefit. Any payments should be disclosed in subject recruitment (4e). The only benefit, if it could be considered one, that subjects would receive is the satisfaction of being asked to think critically about the benefits and limitations of an engineering tool (FEA) and then having an opportunity to voice their thoughts. (Sandians often seem to enjoy such opportunities.) Sandia would receive the benefit of gaining a detailed account of how FEA was used on two real projects with aggressive schedules, and how team members' perceptions of the technical abilities and limitations of FEA affected their thinking and decision-making. Applied correctly, this understanding could in turn be used to help improve the use of FEA on small- to medium-sized projects at Sandia and properly scope its role in the product design and development process. The benefits to society, if any, would be indirect, such as improved engineering practices and efficiency within a Department of Energy National Laboratory and/or extension of this understanding to the private sector.

b. Explain why the risks are reasonable in relation to the anticipated benefits to subjects and the importance of the knowledge that may reasonably be expected to result. The risks are reasonable in relation to the potential benefits for two reasons: (1) because the risks are very straight-forward to mitigate against (described above), and (2) the benefit of this sort of reflective and critical thinking about the what factors affect the usefulness of FEA as an engineering tool, the advantages and disadvantages of using it, and how the information obtained from it is assimilated by the design team members into their thinking, is a critical part of achieving an optimal implementation of FEA in our multi-disciplinary product development efforts.

7. Privacy

HIPAA (*see notes at end of this application*)

Protected Health Information (PHI) is a subset of individually identifiable health information, including demographic data collected from an individual, that relates to the past, present, or future physical or mental health or condition of an individual; the provision of health care to an individual;

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or the past, present, or future payment for the provision of health care to an individual; and in which it is reasonably believed the information can be used to identify the individual.

a. Does this project involve the use or disclosure of PHI? Yes ☐ No ☒

If no, skip to PII (next page)

If PHI is being collected then either:

- HIPAA Authorization must be included in the consent form; or
- HIPAA Authorization <u>Waiver</u> must be justified (*attach form HSB-105*).

b. Is a written HIPAA Authorization required?

☒ Not Applicable – PHI is not being collected

☐ No, HIPAA Authorization <u>Waiver</u> is being requested (*attach form HSB-105*)

If neither of the above two choices applies, then ☐ Yes, HIPAA Authorization is required. Contact the HSB Office for more information.

Personally Identifiable Information (PII)

I have reviewed the DOE Requirements for PII on the HSB web site. Yes ☒ No ☐

c. Will you collect any personally identifiable information (PII)? Yes ☐ No ☒

Explain why this is, or is not, necessary. Only the first names of the participants will be collected during the interviews. No other personal information or PII is needed for the research.

d. Will any direct identifiers be maintained in order to contact participants should information affecting safety and participation in the study be discovered following their participation? Yes ☐ No ☒

e. Will you retain a link between study code numbers and direct identifiers? Yes ☐ No ☒

Explain why this is, or is not, necessary This study only involves two rounds of interviews with each of 9 members of a design team. Only their first names are needed in the course of conducting the interviews. I know their last names (because we are colleagues) but this is not needed for the study, nor will it be included in the data collected during the interviews.

If yes, describe the link, who will maintain it, who will have access to it, and how long you will keep this link. _N/A____

f. Describe how you will protect data against disclosure to the public or to other researchers or non-researchers. The audio/video recordings of the interviews will be maintained exclusively on the Sandia Restricted Network until such time as interview transcripts can be generated. Transcription should be completed in full by April 2013, at which time all interview recordings will be deleted. Any portions of the interview transcripts published as part of the PI's PhD dissertation will use pseudonyms for all interview participants.

g. List who (other than members of the research team) will have access to data. No one other than the PI will have access to the interview recordings.

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h. Do you anticipate using any data from this study for other studies in the future?
Yes ☐ No ☒

If yes, explain and include this information in the consent form.

8. Data/Specimen Management

a. Who will collect the data or specimens? Three colleagues from Stanford University have agreed to assist the PI by conducting the interviews, in order to maximize the objectivity of the data collection and to minimize the possibility for coercion (since I am a colleague of the interview participants). The researchers are: Dr. Sheri Sheppard, Professor of Mechanical Engineering; Samantha Brunhaver, Ph.D. Candidate, Mechanical Engineering, and Dr. Helen Chen, Center for Design Research.

b. What will happen to the data at the end of the study? Will results be published? If so, where, and in what form (e.g., aggregate data only)? The interviews will be conducted using online videoconferencing software (Microsoft Lync), with the study participants located at Sandia National Laboratories in Livermore, California, and the interviewers located at Stanford University in Palo Alto, California. Audio and video will be recorded during the interviews, for the purpose of generating interview transcripts. Once interview transcripts are generated, the audio/video recordings will be destroyed. All (or perhaps portions) of the interview transcripts may be published as part of the PI's PhD dissertation research.

c. Federal law requires all records related to human subject research be retained for 3 years after study completion. However, all PI records related to human subject research **must be retained for 75 years after completion of the study** in compliance with a DOE moratorium on destruction of such records (see *SNL Record Retention and Disposition Schedul*e, CPR400.2.13.14, Appendix A (Record Series # HR-102-212-000). If this moratorium is lifted, record retention will revert to the 3-year standard.

Describe your process for ensuring records from this study will be properly stored for 75 years. The 75 year requirement does not apply since this study will not collect Personally Identifiable Information.

9. Other Considerations

a. Is any part of this study **classified**? Yes ☐ No ☒

If yes, explain which part. ______

Will this study involve sensitive or protected unclassified information? Yes ☐ No ☒

b. Does this work meet the DOE definition of **Human Terrain Mapping** (HTM)? Yes ☐ No ☒

c. Will you need access to subjects' personal records for screening purposes or during this study, or will you receive such information from a data repository?
Yes ☐ No ☒

If yes, specify types of records, how you will access them, what information you will take from the records and how you will use them. ______________________

d. Will you make **audio or video recordings** or photographs of subjects? Yes ☒ No ☐
If yes, this information must be included in the consent form.

If yes, describe what type of recordings you will make, how long will you keep them, and if anyone other than the members of the research team will be able to see them. The interviews will be conducted using online videoconferencing software (Microsoft Lync), which will also be used to acquire audio and video recordings of the interviews, for the purpose of generating interview transcripts. Once interview transcripts are generated, the audio/video recordings will be destroyed. All (or perhaps portions) of the interview transcripts may be published as part of the PI's PhD dissertation research.

e. Identify **circumstances for terminating** the study**.** The study would be terminated if the PI were to have a serious health issue and could not continue with the research. The second round of interviews (est. Jan-Feb 2013) may be terminated if the design project constituting the second case study is delayed or canceled.

f. Does anyone who is responsible for tasks related to the design, conduct or reporting, including obtaining informed consent of this study, have a personal or financial **conflict of interest** in this study? Yes ☐ No ☒

If yes, please describe the potential conflict, including the extent of the interest in the sponsor, equipment, or software being tested. ______________________

10. Informed Consent Process

a. Describe the full process of consent including plans for advertising, recruiting, and how and where the consent process will take place. Explain how it will be structured to enhance independent and thoughtful decision-making. What will the person obtaining consent say? I will meet with each participant individually and describe the research (most of them are already partially familiar with it, since they are my colleagues and they know I am participating in the UPT Program). I will ask them if they would be interested/willing to participate in the interviews. I will verbally summarize the protocol so they have a reasonable idea of what to expect and can make an informed decision about participating. I will describe to them the overall research questions I am to answer (again, many are already familiar with my research) and how/why their participation would be useful and how the interview results/transcripts will be used. I will answer any clarifying questions they have. If they wish to see a copy of the protocol that will be used to guide the interviews, I will provide that to them.

b. Is a written HSB Informed Consent form required for this study?

☒ Yes, standard informed consent document(s) attached.

☐ No, a waiver of informed consent is being requested. (*attach form HSB-105*)

c. Who will obtain consent? The principal investigator.

d. Will the nature of the research or other factors potentially inhibit a subject's desire/ability to withdraw from participation? If so, what steps have been taken to minimize this? No.

e. How will you provide prospective subjects sufficient opportunity and time to consider whether or not to participate. I will ensure they have at least one week to consider the request before I follow-up on the initial request (assuming they do not consent immediately, or have not gotten back to me after one week).

f. How you will minimize the possibility of coercion or undue influence. I will emphasize that their participation is voluntary and not required in any way. I will emphasize that if for any reason they do not wish to participate, they can decline. I will emphasize that if at any time during the interviews or the study they wish to cease participation, they will be free to do so. I will emphasize that their participation is not essential for the research project, so that they do not feel unduly obligated to participate.

g. Will any information about the research be withheld from potential or participating subjects? Yes ☐ No ☒ If yes, describe the debriefing process. ________________________________

h. What happens to data if a subject decided to withdraw? If a subject withdraws from the study, any data that had been collected so far for that participant (e.g., a partial interview recording) would not be used for the study, and instead would be destroyed.

11. Outcome

a. What results do you anticipate? It is anticipated that the design team members will gain an improved understanding of the abilities, limitations, and nuances of using FEA to perform vibration and shock modeling. This will be evidenced by design team members asking detailed questions about the FEA results, demonstrating critical thinking in terms of assimilating the information obtained via FEA with that obtained from other sources, and including the use of FEA in their overall decisions of how best to utilize finite project resources while addressing the most pressing design and program risks with a graded level of rigor. It is also anticipated that some will shows signs of having gained an increased fondness for the use of FEA, while others may demonstrate a reduced confidence in FEA, either as a method outright, or as a tool on the types of design projects represented by these case studies.

b. What are your criteria for success or failure? The study will be deemed a success if any measureable differences or trends can be drawn out of the data collected during the interviews that help answer the research questions listed in Section 2d. Conversely, the study would be deemed a failure if no trends or inferences could be drawn out of the data collected during the interviews for use in answering the research questions.

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c. When will the study be completed? It is anticipated that the study will be completed on or around June 2013.

Information Required for HSB Review

Items **1-7 are mandatory** for all Expedited and Full Board Reviews. (*see form HSB-100*)
8-12 are **only if applicable**.

1. Completed application (this form)
2. Complete copy of the funding proposal (WFO, LDRD, NIH, etc.)
3. Abstract (maximum 750 words)
4. Informed Consent form
5. HSB Review Levels (form HSB-100)
6. All questionnaires, surveys, and any other printed or screen information that subjects will see
7. Recruitment materials (advertisements, flyers, contact letters, phone or email scripts, recruitment web site template, etc.)

Only if applicable:

8. Request for Waiver (form HSB-105)
9. Any pertinent reviews of this proposed work: ES&H, Hazard Assessments, NEPA, or related safety approvals
10. Data Transfer Agreements or other agreements/contracts with collaborating institutions
11. Justification for any waiver requested (form HSB-108)
12. Copy of any other IRB review or approval

Note: All HSB forms & templates are located on the HSB web site:

Sandia National Laboratories

Operated for the U.S. Department of Energy by
Sandia Corporation
Albuquerque, New Mexico 87185-1019

SNL HSB

date: July 24, 2012

to: Jerrod Peterson, MS 9102

Terry

from: Terry J. Reser, MS-1015
Human Studies Board Administrator

subject: **"Integrating the use of finite element analysis into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock inputs" study (SNL1245) is Exempt**

Sandia's Human Studies Board has reviewed all the information submitted for this proposed activity and has determined that the activity does constitute human subject research, but is Exempt from further HSB review under 10 CFR 745.101(b)(2):

> Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless:
>
> (i) Information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and
>
> (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

Please note that this determination is based on the current scope and description of the proposed study. If the scope of work or proposed activities should change, you must notify the HSB immediately. Also, please notify me when this study ends, so we can close out this file.

Even though this study is currently exempt from further HSB review, you are required to understand and carry out your responsibilities as PI for protecting human subjects of research. These responsibilities, as well as those of the HSB, are described in detail in the *HSB Procedures Manual* (http://www.sandia.gov/health/hsb/HSBmanual.pdf).

Enclosed you will also find the approved Informed Consent form, which contains an HSB approval stamp on each page indicating the expiration date of the approval. **Only unaltered copies of this approved form may be used to document consent from human subjects.**

If you have any questions or concerns regarding this determination, please don't hesitate to contact me at 845-9171 or treser@sandia.gov.

Exceptional Service in the National Interest

Prospective research subject -- *Read this consent form carefully. It describes the purpose of the research, specifies exactly what you will do in the study & what information will be collected. It also explains the risks & benefits of your participation, and identifies what steps will be taken to protect your health, your privacy, and the confidentiality of the data gathered. Ask as many questions as you like before you decide whether to participate in this study. You will receive a signed copy of this form.*

RESEARCH SUBJECT CONSENT FORM

Title: ***Integrating the use of finite element analysis into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock inputs (SNL1245)***

Date: ***06/12/2012***

Sponsor: ***Sandia National Laboratories University Part-Time Program***

Principal Investigator: ***Jerrod Peterson, 08135, MS9102, 925-294-6197***

Other Investigator(s): ***Dr. Sheri Sheppard, Samantha Brunhaver, and Dr. Helen Chen, all of Stanford University***

Organization/Location: **Sandia National Laboratories, MS-9102**
Livermore, CA 94551

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1. PURPOSE OF RESEARCH STUDY:

This study will investigate the qualitative aspect of finite element analysis [FEA] modeling techniques for engineering design purposes -- how the use of these techniques impacts the design process and the thinking of the design team members. To assess this impact, one-on-one interviews with the design team members will ask about your participation and experiences on two recent design projects at Sandia that are being used as case studies in the Principal Investigator's (PI) dissertation research. The purpose of the case studies is both to demonstrate the use of the developed FEA modeling techniques, and to investigate how the use of these techniques in a project setting affects the design process and the design team members.

2. PROCEDURE:

Participants will be asked if they are willing to participate in an interview that is expected to last about 30-60 minutes and will occur sometime during July or August 2012. The interviews will be conducted online using Microsoft Lync software, during working hours, at a time that is convenient for the study

APPROVED by SNL
Human Studies Board
Effective 7-24-12
Expires 7-23-2013

participants, who will be located at Sandia National Laboratories in Livermore, California. The interviewer will be one of three researchers at Stanford University in Palo Alto, California.

The interviews will be conducted using a guided interview protocol, which will be made available to you prior to the interviews. The interview protocol has been designed by the PI to ask about your participation and experiences on two recent design projects. You will be asked several questions dealing with your perception of the benefits and limitations of using FEA in the context of real product development efforts.

Audio and video will be recorded during the interviews for the purpose of generating interview transcripts. Once interview transcripts are generated, the audio/video recordings will be destroyed. Selected excerpts from the interview transcripts may be published as part of the PI's Ph.D. dissertation research.

Some or all of the study participants may be invited to participate in a second interview, also expected to last about 30-60 minutes, which would be conducted sometime around January-February 2013. As with the first interview, participation in a second interview will be strictly voluntary. Participation in the first round of interviews would not obligate the interviewees to participate in the second round of interviews.

Analysis of the interview transcripts and incorporation into the final research report is expected to continue until approximately June 2013.

3. POSSIBLE RISKS/DISCOMFORTS:

It would be a moderately serious risk to participants to widely disseminate participants' names, the fact that they work at Sandia National Laboratories, and/or the details of the projects that are the focus of the case studies. To prevent this from occurring, the final (published) form of the research report will use "participant numbers" for all participants. First names will be given to the three researchers at Stanford to facilitate the interviews. The name/details of the program that the case-study participants are working on will not be included in the research report nor given to the interviewers from Stanford, and the names will be stripped out of the transcripts.

It will be important for participants to refrain from discussing any classified or sensitive (e.g., Official Use Only) information during the interviews. To help mitigate the risk of inadvertently discussing such information, all participants will be given a copy of the guided interview protocol in advance of the actual interviews, so that they can review it and think about their answers ahead of time, if desired.

To help ensure privacy, all participants are asked to please refrain from discussing responses with each other or with other members of the workforce.

4. POSSIBLE BENEFITS AND COMPENSATION:

The only benefit for participants is the intangible benefit of being asked to think critically about the benefits and limitations of an engineering tool (FEA) and then having an opportunity to voice their thoughts. Beyond this, participants should not expect to receive any benefits or compensation for participating in this study.

Sandia Corporation will receive the benefit of gaining a detailed account of how FEA was used on two real projects with aggressive schedules, and how team members' perceptions of the technical abilities and limitations of FEA affected their thinking and decision-making. The benefits to society, if any, would be indirect, such as improved engineering practices and efficiency within a Department of Energy National Laboratory and/or extension of this understanding to the private sector.

5. AVAILABLE MEDICAL TREATMENT FOR ADVERSE EXPERIENCES:

Participation in this study does not introduce any likelihood of injury.

APPROVED by SNL
Human Studies Board
Effective 7-24-12
Expires 7-23-2013

6. ALTERNATIVE TO PARTICIPATION:

Your alternative is simply not to participate in this study. This study is voluntary and declining to participate will not affect you in any way.

7. CONFIDENTIALITY OF DATA / SPECIMENS:

Upon completion of each interview, the audio/video recordings will be used to generate interview transcripts, at which point the audio/video recordings will be destroyed. The interview transcripts will be associated only with the appropriate "participant number."

Selected excerpts from the interview transcripts may be published for scientific purposes but will not give your name or any identifiable references to you. However, your name, any audio or video recordings of the interviews, and/or interview transcripts may be inspected by the sponsor, by any relevant governmental agency (e.g., U.S. Department of Energy), by the Sandia Human Studies Board or by the persons conducting this study, provided that such inspectors are legally obligated to protect any identifiable information from public disclosure, except as otherwise authorized or required by law.

8. TERMINATION OF STUDY:

The study will be terminated if anyone outside or inside of Sandia (including Management) attempts to sequester the interview transcripts inappropriately.

You are free to withdraw from the study at any time (e.g., before, during, or after the interview) without penalty. If you choose to withdraw, please notify the Principal Investigator immediately.

Your participation in this study may be ended by the Principal Investigator at any time. Additionally, the sponsor reserves the right to terminate the study at any time.

9. AVAILABLE SOURCES OF INFORMATION:

If you have questions about the study or the procedures, (or you experience any unanticipated effects as a result of being in this study), you can contact the following people:

Jerrod Peterson, Principle Investigator
Sandia National Laboratories
(925) 294-6197, jppeter@sandia.gov

Terry Reser, Subject advocate
Sandia National Laboratories
(505) 845-9171, treser@sandia.gov

APPROVED by SNL
Human Studies Board
Effective 7-24-12
Expires 7-23-2013

10. AUTHORIZATION:

Your signature below signifies the following:

- You have read this consent form and had your questions about this study answered to your satisfaction.
- You voluntarily choose to participate in this study.
- Your consent does not take away any legal rights in the case of negligence or other legal fault of anyone who is involved in this study.
- Nothing in this consent form is intended to preempt any applicable federal, state or local laws regarding informed consent.
- You will receive a signed and witnessed copy of this form.

____

Participant Name *(please print)*

______________________________ ____________

Participant Signature Date

____

Witness Name *(please print)*

______________________________ ____________

Witness Signature Date

APPROVED by SNL
Human Studies Board
Effective 7-24-12
Expires 7-23-2013

Sandia National Laboratories

Operated for the U.S. Department of Energy by
Sandia Corporation
Albuquerque, New Mexico 87185-1019

date: August 22, 2013

to: Jerrod Peterson, MS 9102

Terry

from: Terry J. Reser, MS-1015
Human Studies Board Administrator

subject: **Amendment to "Integrating the use of finite element analysis into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock inputs" study (SNL1245) is Approved**

Sandia's Human Studies Board has reviewed the proposed amendment to this currently approved study and has determined that the changes pose no additional risk to subjects. Additionally, this work continues to meet the criteria to be Exempt from further HSB review at this time under 10 CFR 745.101(b)(2):

> Research involving the use of educational tests (cognitive, diagnostic, aptitude, achievement), survey procedures, interview procedures or observation of public behavior, unless:
>
> (i) Information obtained is recorded in such a manner that human subjects can be identified, directly or through identifiers linked to the subjects; and
>
> (ii) any disclosure of the human subjects' responses outside the research could reasonably place the subjects at risk of criminal or civil liability or be damaging to the subjects' financial standing, employability, or reputation.

Please note that this determination is based on the current scope and description of the proposed study. If the scope of work or proposed activities should change, you must notify the HSB immediately. Also, please notify me when this study ends, so we can close out this file.

Even though this study is currently exempt from further HSB review, you are required to understand and carry out your responsibilities as PI for protecting human subjects of research. These responsibilities, as well as those of the HSB, are described in detail in the *HSB Procedures Manual* (http://www.sandia.gov/health/hsb/HSBmanual.pdf).

Since this amendment does not result in any changes to the consent form, the currently approved version (effective 7/23/13) is still valid. **Only unaltered copies of this approved form may be used to document consent from human subjects.**

If you have any questions or concerns regarding this determination, please don't hesitate to contact me at 845-9171 or treser@sandia.gov.

cc: HSB file SNL1245

Exceptional Service in the National Interest

***Prospective research subject --** Read this consent form carefully. It describes the purpose of the research, specifies exactly what you will do in the study & what information will be collected. It also explains the risks & benefits of your participation, and identifies what steps will be taken to protect your health, your privacy, and the confidentiality of the data gathered. Ask as many questions as you like before you decide whether to participate in this study. You will receive a signed copy of this form.*

RESEARCH SUBJECT CONSENT FORM

Title: ***Integrating the use of finite element analysis into the conceptual design process for evaluating the response of electronics packaging design concepts to vibration and shock inputs (SNL1245)***

Date: ***06/12/2012***

Sponsor: ***Sandia National Laboratories University Part-Time Program***

Principal Investigator: ***Jerrod Peterson, 08135, MS9102, 925-294-6197***

Other Investigator(s): ***Dr. Sheri Sheppard, Samantha Brunhaver, and Dr. Helen Chen, all of Stanford University***

Organization/Location: **Sandia National Laboratories, MS-9102 Livermore, CA 94551**

---

1. PURPOSE OF RESEARCH STUDY:

This study will investigate the qualitative aspect of finite element analysis [FEA] modeling techniques for engineering design purposes -- how the use of these techniques impacts the design process and the thinking of the design team members. To assess this impact, one-on-one interviews with the design team members will ask about your participation and experiences on two recent design projects at Sandia that are being used as case studies in the Principal Investigator's (PI) dissertation research. The purpose of the case studies is both to demonstrate the use of the developed FEA modeling techniques, and to investigate how the use of these techniques in a project setting affects the design process and the design team members.

2. PROCEDURE:

Participants will be asked if they are willing to participate in an interview that is expected to last about 30-60 minutes and will occur sometime during July or August 2012. The interviews will be conducted online using Microsoft Lync software, during working hours, at a time that is convenient for the study

APPROVED by SNL Human Studies Board Effective 7-23-13 Expires 7-22-2014 participants, who will be located at Sandia National Laboratories in Livermore, California. The interviewer will be one of three researchers at Stanford University in Palo Alto, California.

The interviews will be conducted using a guided interview protocol, which will be made available to you prior to the interviews. The interview protocol has been designed by the PI to ask about your participation and experiences on two recent design projects. You will be asked several questions dealing with your perception of the benefits and limitations of using FEA in the context of real product development efforts.

Audio and video will be recorded during the interviews for the purpose of generating interview transcripts. Once interview transcripts are generated, the audio/video recordings will be destroyed. Selected excerpts from the interview transcripts may be published as part of the PI's Ph.D. dissertation research.

Some or all of the study participants may be invited to participate in a second interview, also expected to last about 30-60 minutes, which would be conducted sometime around January-February 2013. As with the first interview, participation in a second interview will be strictly voluntary. Participation in the first round of interviews would not obligate the interviewees to participate in the second round of interviews.

Analysis of the interview transcripts and incorporation into the final research report is expected to continue until approximately June 2013.

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Sandia Corporation will receive the benefit of gaining a detailed account of how FEA was used on two real projects with aggressive schedules, and how team members' perceptions of the technical abilities and limitations of FEA affected their thinking and decision-making. The benefits to society, if any, would be indirect, such as improved engineering practices and efficiency within a Department of Energy National Laboratory and/or extension of this understanding to the private sector.

5. AVAILABLE MEDICAL TREATMENT FOR ADVERSE EXPERIENCES:

Participation in this study does not introduce any likelihood of injury.

APPROVED by SNL
Human Studies Board
Effective 7-23-13
Expires 2-22-2014

6. ALTERNATIVE TO PARTICIPATION:

Your alternative is simply not to participate in this study. This study is voluntary and declining to participate will not affect you in any way.

7. CONFIDENTIALITY OF DATA / SPECIMENS:

Upon completion of each interview, the audio/video recordings will be used to generate interview transcripts, at which point the audio/video recordings will be destroyed. The interview transcripts will be associated only with the appropriate "participant number."

Selected excerpts from the interview transcripts may be published for scientific purposes but will not give your name or any identifiable references to you. However, your name, any audio or video recordings of the interviews, and/or interview transcripts may be inspected by the sponsor, by any relevant governmental agency (e.g., U.S. Department of Energy), by the Sandia Human Studies Board or by the persons conducting this study, provided that such inspectors are legally obligated to protect any identifiable information from public disclosure, except as otherwise authorized or required by law.

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The study will be terminated if anyone outside or inside of Sandia (including Management) attempts to sequester the interview transcripts inappropriately.

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Terry Reser, Subject advocate
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Human Studies Board
Effective 7-23-13
Expires 7-22-2014

10. AUTHORIZATION:

Your signature below signifies the following:

- You have read this consent form and had your questions about this study answered to your satisfaction.
- You voluntarily choose to participate in this study.
- Your consent does not take away any legal rights in the case of negligence or other legal fault of anyone who is involved in this study.
- Nothing in this consent form is intended to preempt any applicable federal, state or local laws regarding informed consent.
- You will receive a signed and witnessed copy of this form.

____
Participant Name *(please print)*

______________________________ ____________
Participant Signature Date

____
Witness Name *(please print)*

______________________________ ____________
Witness Signature Date

APPROVED by SNL
Human Studies Board
Effective 7-23-13
Expires 7-22-2014

Appendix J: Vibration and Shock Analysis Method

The design models were developed using Pro/Engineer Wildfire 4, which is heavily utilized at Sandia for much of its design and development work. The FEA was conducted using Mechanica, the integrated FEA software available with Pro/Engineer.[26] A Mechanica 'Advanced Analysis' license was required to perform all of the necessary vibration and shock analyses.

The FEA models described in this research use what is often referred to as "structural dynamics" or "linear dynamics"—i.e., the linear-elastic response of the structure to various types of dynamic loading. The term "linear-elastic" refers specifically to material properties, but in reality, a variety of possible sources of nonlinearity in the response of the structure are excluded in order to maintain a linear FEA model. Effects that cannot be captured by such a model include the following:

- material nonlinearities, such as plasticity, hyper-elasticity, creep, and viscoelasticity;
- geometric nonlinearities, such as large strains, large displacements, and stress-stiffening; and
- boundary condition nonlinearities, such as contact and friction.

Clearly, the list of physical effects that cannot be modeled by a simple structural dynamics FEA model is quite long. Even so, for the right type of structure with the right type of loading, such a model can be useful for describing and better understanding the dynamic behavior of the design.

For this product and the FEA models that have been developed, the dynamic loading is of two types. The first is stationary random vibration, typically referred to more succinctly as random vibration. In this type of vibration, the loading is random, but with a frequency content that on average does not change over time. The second type of dynamic loading is referred to as shock, which involves impulse-like acceleration loads that are transient and decay relatively quickly over time. It is worth clarifying that this does not mean a "shock" in the physics-sense of the word, which would involve displacements propagating faster than the speed of sound in the various materials. Nor does it mean loads that are severe enough to induce plastic deformation or ultimate failure of the parts.

[26] Mechanica is now Creo Simulate, and Pro/Engineer Wildfire is now Creo Parametric. Both are made by Parametric Technology Corporation

Mechanica uses the method of modal superposition to compute the response of the structure to vibration or shock loading. The first step in this method is to perform a modal analysis, which predicts the natural frequencies and associated mode shapes of the structure over a specified frequency range. Different limitations exist on the number of natural frequencies that should be calculated, depending on both the type of eigenvalue solution method used by the FEA code, and on the frequency range of interest for the particular vibration or shock analysis. The available software documentation does not state which eigenvalue solution method Mechanica uses, but a simple rule of thumb was presented by Bathe (1996, p. 960, 963) for the subspace iteration method, which is one of the more commonly-used methods. If the maximum frequency of interested is p, the number of eigenvalues that should be computed, q, should be the lesser of either $2p$ or $p + 8$. For the analyses in these case studies, the maximum frequency response of interest was 2 kHz. In the first case study, the modes were computed between 10 Hz and 3 kHz, with 3 kHz being more than sufficient to satisfy the $p + 8$ rule. In the second case study, the $p + 8$ rule was used.

The second step in the method of modal superposition is to apply the dynamic load to the structure. The response of the structure is computed using the natural frequencies and mode shapes computed in the first step as a basis for the solution. For random vibration, the load is specified using an acceleration power spectral density (PSD), which is also how this type of load is specified for laboratory testing. For shock, the load is an acceleration time history of the shock pulse, which is generated analytically (using other software) to satisfy a specified shock response spectrum (SRS). The FEA software then calculates a variety of outputs, including the response of the structure at any number of specified measurement locations. For random vibration, the output at each of these measurement locations is an acceleration PSD. All PSDs were computed in increments of 10 Hz over the input range. For shock, the output at each measurement location is an acceleration time history, which is computed in increments that are determined automatically by the software.

For context, other noteworthy FEA codes for conducting structural dynamics analysis using the method of modal superposition are the commercial codes Nastran and Abaqus, as well as the Sandia-proprietary code Salinas. However, unlike these more powerful codes, Mechanica has limited capabilities for utilizing parallel processors.

For the modal analyses, the Mechanica option "single pass adaptive" was used to control the convergence iterations. With this option, an initial solution is generated in which all elements are third-order. Using the global RMS stress error as the convergence criteria, the polynomial order of elements with high stress error is increased up to a polynomial order as high as 9, and the analysis is repeated once. The final stress error value is reported for each mode.

Appendix K: Case Study 1 FEA Model Details

The following tables provide additional information on various details and performance metrics of the FEA models used in the first case study.

Case study 1: Material properties and element types					
Part	**Material**	**Element type**	**[Effective] Density ρ (lbm/in^3)**	**Young's modulus E (psi)**	**Poisson's ratio ν**
Main housing	Brass	Solid	0.304	15×10^6	0.34
End cover to which motherboard attaches					
Other end cover (i.e., for mounting electronics module in Concepts 1 and 2)	Stainless steel	Solid	0.283	30×10^6	0.29
Motherboard and 4X plug-in circuit boards, loaded with small discrete components [1,2]	FR4 laminate	Shell	0.105	3.38×10^6	0.172
4X Plug-in card frames	Aluminum alloy	Solid	0.0975	10×10^6	0.33
Electronics module walls					
Electronics module potting [1,3]	Polyuretha ne foam	Solid	0.028	4×10^3	0.25
8X Shell of electrical connectors on plug-in cards and motherboard [1]	Aluminum alloy	Beam	0.244	10×10^6	0.3
4X Mechanical coupling between plug-in cards and motherboard at electrical connectors	---	Rigid Link	---	---	---
4X External electrical connectors on motherboard at end cover [1,4]	Various	Solid	0.081	2×10^6	0.25
8X O-rings between plug-in card frame shoulders and main housing [5]	Neoprene (com-pressed)	Solid	0.070	5×10^3	0.45
8X Screws connecting plug-in card shoulders to main housing	Alloy steel	Solid	0.283	30×10^6	0.29

Notes:
[1] Effective ρ selected to give overall correct weight.
[2] E, ν from FR4 tensile tests conducted at Sandia National Laboratories, May 2011.
[3] E, ν estimated based on similar rigid polyurethane foams.
[4] E, ν roughly estimated based on use of liquid crystal polymer for main body of connector.
[5] E taken as linearized value from corresponding point on calculated stress-strain curve, based on measured torque-displacement data for the compressed O-rings.

Case 1: Damping, boundary conditions, and connections between parts		
Description	**Where used**	**Initial estimate / configuration**
Damping [1]	All modes	3%
Boundary condition to next-assembly	Surface of flange that mates with next-assembly	Entire surface is fixed in all 6 DOFs [2]
Boundary conditions for connections between parts	Main housing to each end cover	Entire mated surface "bonded" together [3]
	Mechanical coupling between plug-in cards and motherboard at board-to-board electrical connectors	Used Mechanica "Rigid Link" elements between 10 pairs of points along each part
	All other part-to-part connections, e.g., • Plug-in cards to frames • Plug-in card frames to main housing • Motherboard to adjacent end cover • Motherboard to 4X external electrical connectors at end cover • 4X external electrical connectors to end cover • Electronics module to adjacent end cover (Concepts 1 & 2) or main housing (Concept 3)	"Bonded" at fastener locations and "free" elsewhere [4]

Notes:
[1] Based on limited historical data for similar, unpotted electronics assemblies.
[2] Causes the entire surface to be treated as perfectly rigid.
[3] Similar to replacing the bolted interface with a 'welded' connection over the entire mated area.
[4] Similar to replacing the bolted interface with 'spot welds' at the fastener locations, with a diameter roughly equal to that of the fastener.

Case 1: Summary of FEA model size and computer details				
Model size / computer details	**Concept 1 initial model**	**Concept 2 initial model**	**Concept 3 initial model**	**Concept 1 refined model**
No. elements	7581	7692	8082	16178
No. equations: 1st pass	145440	147126	157560	286992
No. equations: 2nd pass	245997	283521	259683	436365
Max. polynomial order: 1st pass	3	3	3	3
Max. polynomial order: 2nd pass	9	9	9	9
CPU time: modal	1.6 hrs	2.2 hrs	1.7 hrs	1.1 hrs
CPU time: 3 vibration profiles, 3 directions each	24.4 hrs	26.1 hrs	26.1 hrs	17.4 hrs
CPU time: 3 shock profiles, 3 directions each	11.5 hrs	16.0 hrs	12.6 hrs	25.7 hrs
CPU time: total	37.6 hrs	44.3 hrs	40.3 hrs	44.3 hrs
Operating system	32-bit Windows XP			64-bit Windows 7
Processors	Dual core 3-GHz			Dual 6-core 2.67-GHz
RAM	3.6 GB			24 GB

Case 1: Total mass participation factors				
Direction	**Concept 1 initial model**	**Concept 2 initial model**	**Concept 3 initial model**	**Concept 1 refined model**[27]
X	25.0%	22.7%	29.3%	77.6%
Y	59.7%	59.2%	67.7%	75.3%
Z	62.8%	62.5%	68.7%	73.2%

Case 1: Comparison of modal analysis convergence results, RMS stress error estimates (% max modal stress)				
Convergence results	**Concept 1 initial model**	**Concept 2 initial model**	**Concept 3 initial model**	**Concept 1 refined model**
Average	2.48%	3.58%	1.52%	2.09%
Maximum	6.00%	10.20%	3.20%	5.40%

[27] To better match the test data, the Concept 1 refined model included a more compliant boundary condition, which also greatly increased the total mass participation factor.

Case 1: Modal analysis convergence results, Concept 1 initial model, RMS stress error estimates (% max modal stress)								
Mode No.	**Freq. (Hz)**	**Stress error**	**Mode No.**	**Freq. (Hz)**	**Stress error**	**Mode No.**	**Freq. (Hz)**	**Stress error**
1	663.1	2.50%	25	1810.4	4.10%	49	2448.8	0.90%
2	666.2	2.00%	26	1868.9	3.90%	50	2461.3	2.50%
3	673.2	2.50%	27	1890.0	1.20%	51	2467.4	1.30%
4	679.1	2.10%	28	1893.1	1.00%	52	2469.1	2.30%
5	1031.8	4.10%	29	1978.4	3.90%	53	2480.0	1.30%
6	1042.6	4.60%	30	2020.8	1.00%	54	2489.2	1.00%
7	1049.0	4.70%	31	2046.6	3.30%	55	2498.9	1.10%
8	1057.9	4.20%	32	2070.3	3.90%	56	2640.0	3.70%
9	1064.3	3.50%	33	2115.9	4.80%	57	2686.2	1.40%
10	1078.8	4.20%	34	2143.0	6.00%	58	2724.0	1.50%
11	1094.1	5.20%	35	2154.3	3.70%	59	2772.2	1.10%
12	1106.5	4.70%	36	2162.1	4.20%	60	2789.3	1.30%
13	1277.8	4.50%	37	2172.3	3.70%	61	2807.8	1.30%
14	1437.9	3.60%	38	2172.9	5.10%	62	2836.7	1.80%
15	1549.1	2.10%	39	2190.5	3.40%	63	2849.1	1.30%
16	1559.6	1.40%	40	2212.0	3.90%	64	2853.8	1.40%
17	1560.3	1.30%	41	2260.8	3.30%	65	2857.1	0.90%
18	1570.5	2.30%	42	2284.2	3.20%	66	2873.2	1.10%
19	1577.5	1.80%	43	2390.6	1.60%	67	2892.5	1.10%
20	1581.8	1.80%	44	2407.7	0.90%	68	2904.6	1.40%
21	1658.3	1.40%	45	2428.6	0.80%	69	2934.8	1.50%
22	1660.8	2.00%	46	2432.5	0.90%	70	2985.3	3.00%
23	1669.6	1.50%	47	2434.7	1.00%	71	2994.9	3.20%
24	1672.2	1.30%	48	2441.5	0.80%			

Case 1: Modal analysis convergence results, Concept 2 initial model, RMS stress error estimates (% max modal stress)								
Mode No.	Freq. (Hz)	Stress error	Mode No.	Freq. (Hz)	Stress error	Mode No.	Freq. (Hz)	Stress error
1	615.3	4.80%	31	1830.3	2.90%	61	2560.6	2.30%
2	619.4	5.70%	32	1840.0	3.20%	62	2574.2	1.70%
3	621.2	5.50%	33	1845.0	3.70%	63	2615.4	3.80%
4	624.2	4.50%	34	1851.6	4.70%	64	2624.6	3.60%
5	1021.2	3.20%	35	1865.6	8.20%	65	2626.4	3.30%
6	1040.7	8.50%	36	1886.0	8.10%	66	2638.5	4.70%
7	1057.5	5.80%	37	1928.8	3.70%	67	2643.0	3.30%
8	1059.4	6.00%	38	1983.9	2.10%	68	2662.3	3.10%
9	1062.2	10.20%	39	2001.0	2.20%	69	2673.7	4.70%
10	1069.2	10.00%	40	2005.7	2.20%	70	2692.9	1.70%
11	1075.7	5.50%	41	2010.6	3.10%	71	2694.3	1.90%
12	1083.8	5.20%	42	2013.0	2.10%	72	2708.9	2.70%
13	1180.9	5.90%	43	2091.9	7.70%	73	2710.2	2.20%
14	1338.3	4.40%	44	2145.7	7.20%	74	2715.5	2.20%
15	1380.7	3.10%	45	2157.7	3.30%	75	2720.9	1.60%
16	1401.5	3.50%	46	2173.8	6.60%	76	2769.0	2.00%
17	1416.8	2.50%	47	2182.8	4.50%	77	2772.2	2.30%
18	1421.5	2.30%	48	2196.2	4.40%	78	2788.7	1.70%
19	1439.6	0.90%	49	2207.6	5.70%	79	2791.2	1.50%
20	1454.1	1.60%	50	2217.2	5.30%	80	2810.6	1.50%
21	1463.8	1.70%	51	2330.9	2.60%	81	2840.1	2.70%
22	1488.4	1.40%	52	2400.3	3.00%	82	2846.6	2.10%
23	1518.3	1.60%	53	2438.4	4.60%	83	2866.8	3.90%
24	1520.7	1.50%	54	2453.5	6.20%	84	2868.6	4.00%
25	1698.9	4.70%	55	2465.6	1.70%	85	2931.6	2.30%
26	1742.2	4.50%	56	2472.6	3.60%	86	2936.6	1.20%
27	1758.0	3.40%	57	2486.6	3.50%	87	2958.0	1.20%
28	1772.0	2.60%	58	2496.7	4.10%	88	2969.4	1.10%
29	1777.4	2.80%	59	2514.9	2.30%	89	2972.9	1.00%
30	1824.2	2.30%	60	2543.1	1.80%	90	2986.1	0.70%

Case 1: Modal analysis convergence results, Concept 3 initial model, RMS stress error estimates (% max modal stress)								
Mode No.	Freq. (Hz)	Stress error	Mode No.	Freq. (Hz)	Stress error	Mode No.	Freq. (Hz)	Stress error
1	465.3	1.30%	26	1473.7	2.40%	51	2378.1	0.90%
2	467.7	1.70%	27	1487.6	2.40%	52	2449.4	2.00%
3	473.2	2.20%	28	1490.7	2.00%	53	2493.4	2.30%
4	477.4	1.90%	29	1494.9	1.80%	54	2505.2	2.00%
5	571.7	2.50%	30	1504.9	2.00%	55	2510.6	2.00%
6	604.6	1.30%	31	1508.3	1.70%	56	2538.9	1.80%
7	606.5	1.30%	32	1515.9	1.70%	57	2539.3	1.70%
8	613.4	1.30%	33	1535.4	1.90%	58	2542.2	1.60%
9	618.1	1.00%	34	1544.7	1.70%	59	2548.9	1.20%
10	837.4	0.30%	35	1558.2	2.00%	60	2557.6	1.30%
11	931.4	1.80%	36	1658.8	2.30%	61	2571.0	1.80%
12	933.3	1.70%	37	1877.2	0.40%	62	2603.9	2.20%
13	941.6	2.00%	38	1878.6	0.70%	63	2656.5	2.00%
14	947.0	1.50%	39	1910.3	3.20%	64	2732.8	0.80%
15	1077.5	1.20%	40	2171.9	1.60%	65	2740.3	0.90%
16	1278.4	0.50%	41	2176.8	1.80%	66	2744.7	0.70%
17	1334.1	2.50%	42	2178.0	1.70%	67	2755.9	0.50%
18	1400.2	0.40%	43	2184.9	1.80%	68	2777.9	1.30%
19	1400.7	0.70%	44	2187.6	1.50%	69	2845.4	1.20%
20	1400.8	0.60%	45	2218.9	2.60%	70	2879.9	1.30%
21	1401.3	0.60%	46	2236.5	2.10%	71	2890.3	2.70%
22	1441.5	1.40%	47	2299.5	0.80%	72	2927.7	1.00%
23	1443.4	1.40%	48	2354.5	0.80%	73	2960.7	0.90%
24	1447.3	1.70%	49	2355.3	0.90%	74	2976.6	0.70%
25	1453.9	1.90%	50	2368.0	1.00%			

Case 1: Modal analysis convergence results, Concept 1 refined model, RMS stress error estimates (% max modal stress)								
Mode No.	**Freq. (Hz)**	**Stress error**	**Mode No.**	**Freq. (Hz)**	**Stress error**	**Mode No.**	**Freq. (Hz)**	**Stress error**
1	539.9	1.90%	30	1647.0	3.50%	59	2465.9	3.00%
2	540.7	1.70%	31	1687.6	2.70%	60	2482.9	1.80%
3	542.6	2.00%	32	1745.4	2.70%	61	2488.5	3.20%
4	545.8	1.60%	33	1793.3	2.30%	62	2499.9	2.30%
5	887.8	3.30%	34	1847.1	1.30%	63	2538.3	3.20%
6	892.7	4.00%	35	1877.3	0.90%	64	2632.1	1.60%
7	896.9	3.70%	36	1912.4	0.90%	65	2689.0	1.90%
8	911.1	3.20%	37	2011.2	0.80%	66	2697.2	2.00%
9	931.6	3.60%	38	2061.0	1.20%	67	2727.0	0.80%
10	933.5	4.10%	39	2101.7	3.50%	68	2765.7	0.90%
11	938.9	4.30%	40	2105.8	4.10%	69	2780.0	0.90%
12	943.9	3.00%	41	2112.1	4.60%	70	2784.9	1.10%
13	1024.2	2.00%	42	2133.4	2.30%	71	2808.5	1.00%
14	1249.3	4.00%	43	2195.1	0.80%	72	2824.0	1.40%
15	1272.3	2.30%	44	2204.7	0.80%	73	2830.3	2.60%
16	1304.4	2.50%	45	2207.2	3.60%	74	2835.7	3.80%
17	1417.9	0.80%	46	2219.7	1.00%	75	2841.6	4.70%
18	1420.3	0.80%	47	2244.7	0.70%	76	2847.4	5.40%
19	1424.6	2.00%	48	2245.9	0.60%	77	2856.2	1.10%
20	1433.2	1.00%	49	2259.6	0.50%	78	2858.1	2.60%
21	1435.7	1.30%	50	2260.3	0.80%	79	2864.2	3.50%
22	1493.5	1.80%	51	2267.4	0.60%	80	2893.0	3.20%
23	1575.1	1.00%	52	2334.7	1.10%	81	2925.2	1.10%
24	1579.6	1.00%	53	2404.7	1.30%	82	2937.4	1.80%
25	1582.3	1.70%	54	2413.2	1.00%	83	2969.5	0.80%
26	1597.9	1.00%	55	2413.9	1.40%	84	2989.8	0.50%
27	1611.8	4.40%	56	2415.6	1.50%	85	2999.8	1.40%
28	1620.8	3.50%	57	2440.7	1.00%			
29	1628.6	3.10%	58	2458.0	2.00%			

Appendix L: Case Study 2 FEA Model Details

The following tables provide additional information on various details and performance metrics of the FEA models used in the second case study.

Case study 2: Material properties and element types

Part	Material	Element type	[Effective] Density ρ (lbm/in^3)	Young's modulus E (psi)	Poisson's ratio ν
2X Battery housings	Aluminum alloy 7075	Solid	0.102	10.4x10^6	0.33
2X Battery trays	Poly-carbonate	Solid	0.0434	0.33x10^6	0.38
48X Battery cells [1]	Various	Solid	0.159	10x10^6	0.33
2X Battery silicone RTV layers	RTV	Solid	0.047	435	0.45
Battery paraffin wax	Paraffin	Solid	0.033	7.4x10^3	0.3
4X Circuit board mounting brackets, bracket cap, and base bracket	Aluminum alloy 6061	Solid	0.0975	10x10^6	0.325
Circuit board enclosure		Solid & shell [2]			
Circuit board enclosure cover and 2X small electronics module housings		Shell			
7X Circuit boards, loaded with small discrete components [1,3]	Polyimide laminate	Shell	0.08	4x10^6	0.19
3X Compressible thermally-conductive pad [4]	Gap Pad® VO Ultra Soft	Solid	0.077	450	0.15
24X Screws connecting stacked circuit boards to 4X brackets and standoffs, and enclosed circuit boards and enclosure cover to enclosure	Steel	Solid	0.283	29x10^6	0.27
38X Fasteners connecting battery housings, bracket cap to 4X brackets, and battery to 4X brackets, enclosure, and 2X electronics modules		fastener element			
14X Standoffs for mounting stacked and enclosed circuit boards		Solid			

Case study 2: Material properties and element types (continued)					
Part	**Material**	**Element type**	**Description**		
14X Small electrical connectors	Various [5]	Solid	0.098	$10x10^6$	0.3
2X Large filtered connectors and mating connectors		Solid			
8X Board-to-board electrical connectors [1]	Liquid crystal polymer	Beam	0.057	$1.17x10^6$	0.3
2X Small electronics module internal details	Various	Point mass	0.156 lbm, distributed over 20 internal attachment points		
5X Mechanical coupling between board-to-board electrical connectors	---	Spring	k = $1x10^5$ lbf/in, 2x6 arrays of 12 springs per connection for stacked boards, and 2x3 arrays of 6 springs per connector for enclosed boards		

Notes:
[1] Effective ρ selected to give overall correct weight.
[2] Thin-walled portions modeled with shell elements.
[3] A refined estimate for polyimide circuit board material properties is provided in Table 26.
[4] E taken as linearized value from corresponding point on calculated stress-strain curve, based on load-displacement data provided in product data sheet and 25% strain.
[5] Electrical connector effective bulk material properties approximated as that of aluminum.

Case 2: Damping, boundary conditions, and connections between parts		
Description	**Where used**	**Initial estimate / configuration**
Damping [1]	All modes	4%
Boundary condition to next-assembly	8X locations on battery flanges where attachment to next-assembly occurs	Fixed in all 6 DOFs, diameter roughly equal to that of screw head [2]
Boundary conditions for connections between parts	• 2X layers of silicone RTV to 2X battery housings, 2X polycarbonate trays, and 48 battery cells • Paraffin wax to 2X battery housings and 2X polycarbonate trays • Small electrical connectors around edges of boards, to circuit boards • Mating electrical connectors ('plugged into' electrical connectors on edges of circuit boards and into filtered connectors)	Entire mated surface "bonded" together [3]

Case 2: Damping, boundary conditions, and connections between parts (continued)

Description	Where used	Initial estimate / configuration
Boundary conditions for connections between parts	• Compressed thermally-conductive pad between 2X small electronics modules and circuit board enclosure, and between battery housing and bracket at base of stacked circuit boards • Enclosure cover to adjacent enclosed circuit board	Entire mated surface "bonded" together [3]
	• 48X battery cells to paraffin wax and 2X polycarbonate trays • Edge of enclosure cover to enclosure	Free interface
	• Battery housings to each other • Bracket cap to 4X brackets • Battery to 4X brackets, circuit board enclosure, and 2X electronics modules	Free interface, connected with fastener elements
	• Stacked circuit boards to 4X brackets and standoffs • enclosed circuit boards to enclosure and standoffs	Free interface, connected as shown in Figure 53
	Mechanical coupling between adjacent stacked circuit boards (3 locations) and adjacent enclosed circuit boards (2 locations)	Spring elements between 12 pairs of points for stacked boards, and 6 pairs of points for enclosed boards
	All other part-to-part connections, e.g., • 2X filtered connectors to middle enclosed circuit board • 2X small electronics modules to battery housing	"Bonded" at fastener locations and "free" elsewhere [4]

Notes:
[1] Based on limited historical data for similar, unpotted electronics assemblies, including Case Study 1.
[2] Causes just the 8X circular regions to be treated as perfectly rigid.
[3] Similar to replacing the bolted interface with a 'welded' connection over the entire mated area.
[4] Similar to replacing the bolted interface with 'spot welds' at the fastener locations, with a diameter roughly equal to that of the fastener.

Case 2: Summary of FEA model size and computer details		
Model size / computer details	**Detailed battery model (used for vibration)**	**Simplified battery model (used for shock)**
No. elements	38647	25896
No. equations: 1st pass	669680	478079
No. equations: 2nd pass	994069	772848
Max. polynomial order: 1st pass	3	3
Max. polynomial order: 2nd pass	9	9
CPU time: modal	3.1 hrs	1.4 hrs
CPU time: 3 vibration profiles, 3 directions each	45.2 hrs	---
CPU time: 3 shock profiles, 3 directions each	---	556.6 hrs
CPU time: total	48.3 hrs	558.0 hrs
Operating system	64-bit Windows 7	
Processors	Dual 6-core 2.67-GHz	
RAM	24 GB	

Case 2: Total mass participation factors		
Direction	**Detailed battery model (used for vibration)**	**Simplified battery model (used for shock)**
X	71.7%	69.9%
Y	73.9%	65.5%
Z	72.5%	62.5%

Case 2: Comparison of modal analysis convergence results, RMS stress error estimates (% max modal stress)		
Convergence results	**Detailed battery model (used for vibration)**	**Simplified battery model (used for shock)**
Average	0.76%	0.85%
Maximum	1.60%	2.30%

Case 2: Modal analysis convergence results, detailed battery model (used for vibration), RMS stress error estimates (% max modal stress)								
Mode No.	**Freq. (Hz)**	**Stress error**	**Mode No.**	**Freq. (Hz)**	**Stress error**	**Mode No.**	**Freq. (Hz)**	**Stress error**
1	631.4	0.70%	21	1156.1	0.70%	41	1639.4	0.60%
2	725.5	0.70%	22	1178.8	1.00%	42	1654.7	0.70%
3	751.0	0.90%	23	1209.2	0.80%	43	1687.0	0.90%
4	765.7	0.50%	24	1221.1	0.80%	44	1689.0	0.70%
5	832.8	1.00%	25	1273.4	0.70%	45	1753.4	1.60%
6	851.9	0.70%	26	1279.9	0.90%	46	1798.6	0.50%
7	894.5	0.90%	27	1280.6	0.90%	47	1856.0	0.80%
8	917.9	1.20%	28	1328.4	1.10%	48	1939.1	0.50%
9	923.3	0.40%	29	1331.0	0.60%	49	1940.9	0.70%
10	931.7	0.40%	30	1367.3	0.80%	50	1972.4	0.70%
11	959.4	0.80%	31	1390.5	0.40%	51	1984.3	0.90%
12	1004.2	1.10%	32	1429.2	0.70%	52	2008.1	0.50%
13	1011.8	1.20%	33	1472.1	0.30%	53	2021.1	0.70%
14	1032.2	0.80%	34	1493.8	0.80%	54	2040.7	0.60%
15	1044.0	0.60%	35	1533.7	0.60%	55	2100.8	0.60%
16	1067.2	0.70%	36	1544.5	1.00%	56	2147.6	0.70%
17	1091.2	0.90%	37	1558.5	0.70%	57	2149.7	1.00%
18	1097.5	0.80%	38	1579.3	0.40%	58	2204.0	0.80%
19	1140.0	0.60%	39	1603.1	0.60%	59	2231.4	1.20%
20	1148.3	1.20%	40	1622.8	0.50%			

Case 2: Modal analysis convergence results, simplified battery model (used for shock), RMS stress error estimates (% max modal stress)								
Mode No.	**Freq. (Hz)**	**Stress error**	**Mode No.**	**Freq. (Hz)**	**Stress error**	**Mode No.**	**Freq. (Hz)**	**Stress error**
1	631.4	0.80%	23	1209.8	0.90%	45	1744.9	1.60%
2	726.0	0.80%	24	1222.1	0.80%	46	1798.1	2.30%
3	751.7	0.90%	25	1274.1	0.80%	47	1801.8	0.50%
4	765.5	0.50%	26	1281.5	0.60%	48	1860.5	0.80%
5	833.9	1.00%	27	1283.4	1.30%	49	1911.6	1.00%
6	854.3	0.70%	28	1328.4	1.10%	50	1921.0	1.30%
7	891.6	0.90%	29	1330.8	0.60%	51	1939.6	0.50%
8	909.0	0.80%	30	1369.3	0.80%	52	1942.1	0.80%
9	917.8	1.20%	31	1391.2	0.40%	53	1949.9	1.70%
10	932.2	0.40%	32	1447.7	0.50%	54	1973.6	0.70%
11	959.6	0.80%	33	1472.1	0.50%	55	1983.0	0.90%
12	993.7	0.80%	34	1475.5	0.40%	56	1995.5	0.90%
13	1004.3	1.00%	35	1495.5	0.80%	57	2011.7	0.50%
14	1019.4	1.30%	36	1534.7	0.60%	58	2022.4	0.70%
15	1042.8	1.20%	37	1546.7	1.10%	59	2040.6	0.60%
16	1068.0	0.70%	38	1577.6	0.70%	60	2107.7	0.60%
17	1091.4	0.90%	39	1583.2	0.50%	61	2141.3	0.80%
18	1098.6	0.80%	40	1615.7	0.50%	62	2144.2	1.40%
19	1141.1	0.60%	41	1627.4	0.90%	63	2152.5	1.00%
20	1149.3	1.20%	42	1646.3	0.70%	64	2171.6	0.80%
21	1159.0	0.80%	43	1661.0	0.70%			
22	1179.1	1.00%	44	1688.6	0.70%			

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