Chapter 1.
Introduction and Summary of Methods

Summary: The study's motivation is described, then the overall context for the study is described in a literature review. The study's scope of work is summarized, including conceptual framework, research questions, data sources, and analysis methods, including methods to enhance validity, reliability, and generalizability. This includes an overview of subsequent chapters.

1.1. Motivation: The Debate About Sustainability and Innovation

Much literature has expressed a need for empirical studies on the effectiveness of sustainable design practices. Deutz said, “the benefit of eco-design would be enhanced by rooting it firmly within theoretical design principles... Formulating such an innovative approach requires first understanding current practices of eco-design in industry” [Deutz et al., 2013]. When Harvard economist Michael Porter studied companies improving profits through sustainability-led innovations [Porter and Kramer, 2011], he showed that measuring the results of sustainability efforts are crucial to proving and improving their business viability, environmental impacts, and social impacts [Porter et al., 2011]. Santolaria found that “lack of tangible benefits” ranked as the largest obstacle to “the integration of environmental criteria into strategic plans” but “more than 90% of respondents believe that innovation could be a future catalyst for the integration of eco-design in companies” [Santolaria et al., 2011].

Innovation can be a motivation for companies to adopt sustainable design, and this research also found other benefits. In Knostler's argument that complex systems can only be changed with a combination of vision, skills, incentives, resources, and action plan [Knoster et al., 2000], this thesis aimed to improve design teams' skills and action plans, and investigated the degree to which innovation is an incentive. As Tukker found, “SMEs are generally not willing to pay for environmental consultancy, so private consultancy will only work if direct benefits are obvious, or third parties will bear the costs” [Tukker et al., 2000]. More pointedly, van Hemel found that “internal stimuli are a stronger driving force for ecodesign than external stimuli. The most influential internal stimuli were the opportunities for innovation, the expected increase of product quality and the potential market opportunities“ [van Hemel and Cramer, 2002]. Innovation is highly valued by industry [Kim and Mauborgne, 1999], [Beausoleil, 2012]. Many claim that considering sustainability can improve product innovation [Aronson, 2013], [Keskin et al., 2013], [Charter and Clark, 2007]. However, others have found the pursuit of sustainability to inhibit creativity [Collado-Ruiz and Ghorabi, 2010]. Is this time and effort spent on sustainability a burden, or an investment that pays off in innovation? Or does it pay off in other design value?

1.2. Introduction and Literature Review

Many consumer and industrial product designers, engineers, and businesspeople attempting to create more sustainable products do so using standard Human-Centered Design while thinking about sustainability issues, not by applying actual sustainable design methods. (Note that the design practices used by other industries, such as buildings and software, are different enough from common product design practices that they lie outside the scope of this study.) However, despite most designers attempting to accomplish sustainable design using standard design practices, there are dozens of sustainability-specific design methods, guides, certifications, and other practices to choose from. Sustainability is a complex or "wicked" [Rittel and Webber, 1973] problem; as Page showed mathematically [Page, 2014], a diversity of approaches is more effective for solving complex problems than the raw skill of even the brightest individual or best single approach. Yet, time and money inevitably limit the number of approaches that can be used. Which sustainable design practices are best for what context, and how could they integrate with Human-Centered Design or each other? I argue that designers, engineers, and managers could benefit from understanding better what each design practice offers and how to combine multiple practices, or elements thereof, to maximize their value.

Lofthouse argued the importance of sustainability coming from better design methods or tools: "designers do not have the right mechanisms to support the integration of ecodesign into early product development. Research has suggested that many tools fail because they do not focus on design, but are aimed at strategic management or retrospective analysis" [Lofthouse, 2003]. Knight and Jenkins found that "eco-design techniques may not have been more widely adopted by businesses because such methods are not necessarily generic and immediately applicable…" [Knight and Jenkins, 2009], thus research is needed to find what aspects of different design practices are more or less valuable/applicable to different design teams.

Most literature on sustainable product design practice either treats all sustainable design the same [Sherwin and Bhamra, 1999], [Spangenberg et al., 2010], [Behrisch et al., 2011], [Molenaar et al., 2010], [Cheng et al., 2014], [Bocken et al., 2014], [Keskin et al., 2013], [Storaker et al., 2013], [Anttonen et al., 2013], [Hansen and Große-Dunker, 2013], [Kiron et al., 2013] [Hopkins et al., 2009], or proposes a specific new design method and studies it [Ameli et al., 2016], [Wisthoff and DuPont, 2016], [Uang and Liu, 2013], [Kobayashi, 2006], [Ölundh, 2006], [McDonough and Braungart, 2002], [Benyus, 1997]. However, some recommend different design practices for specific circumstances [White et al., 2013], [Jedlicka, 2009], [Thorpe, 2007], [Steffen, 2006], [Lewis et al., 2001], [Banerjee, 2001]. Some have suggested the need to compare sustainable design practices: "There are a range of eco-design and SPDD tools and methodologies starting to emerge – however there is no common viewpoint" [Charter and Clark, 2007]. "While more companies are becoming interested in the design and development of sustainable products, the means of designing these products are still immature. Primarily, it is difficult to employ potentially disparate processes – in this case, the product design process and sustainable design methods – to meet a single goal" [DuPont and Wisthoff, 2015].

Some have categorized sustainable design practices, in various ways: for example, by their scope and whether they are qualitative or quantitative [Sheldrick and Rahimifard, 2013], [Shedroff, 2009]; by the life-cycle stages they address [Telenko et al., 2008], [Oehlberg et al., 2012]; or by whether they are design methods, guidelines, checklists, or analytical tools [Knight and Jenkins, 2009]. One of the most useful taxonomies is the Living Principles genealogy [Brink et al., 2009], which graphs 31 design practices on axes of "actionable" vs. "visionary" and "selective" vs. "integrated". One of the most extensive studies is Oehlberg's (2012) categorization of 303 principles from 29 different sources by what life-cycle stages they address.

While comparing whole design methods is valuable, in practice, professional designers and engineers do not use design methods as tunnels of process, but as toolboxes. Professionals pull elements from different design methods or design guides opportunistically, often not in order, repeatedly, or skipping steps entirely [Jensen et al., 2010]. This is because "undisciplined process" can be efficient in time and resources [Cross, 2001]. As Homans pointed out, "People who write about methodology often forget that it is a matter of strategy, not of morals. There are neither good nor bad methods, but only methods that are more or less effective under particular circumstances in reaching objectives on the way to a distant goal" [Homans, 1949]. Even the canonical prescriber Pahl admitted real practitioners skip steps in practice [Pahl et al., 1999], and Visser found even when engineers claim they follow a rigid procedure, they are often opportunistic in their actual application of steps in the procedure [Visser, 1990]. One of the engineers interviewed in this study, when asked how they decide to use one design activity or another, said "*most of the time it's when you're stuck.*" One of the designers interviewed said, *"formal design methods are like musical scales; real design practice is jazz."*

Thus, this study will fill an important knowledge gap by deconstructing green product design methods to find and characterize their constituent activities and mindsets, hypothesize their potential synergies and redundancies, and empirically test what activities and mindsets practitioners value for what reasons. Activities are defined as what practitioners do (from writing or sketching to CAD or calculation), while mindsets are defined as what practitioners mentally consider (from individual ideas or points of view to entire paradigms). Figure 1.1 shows these subcomponents of design methods in context.

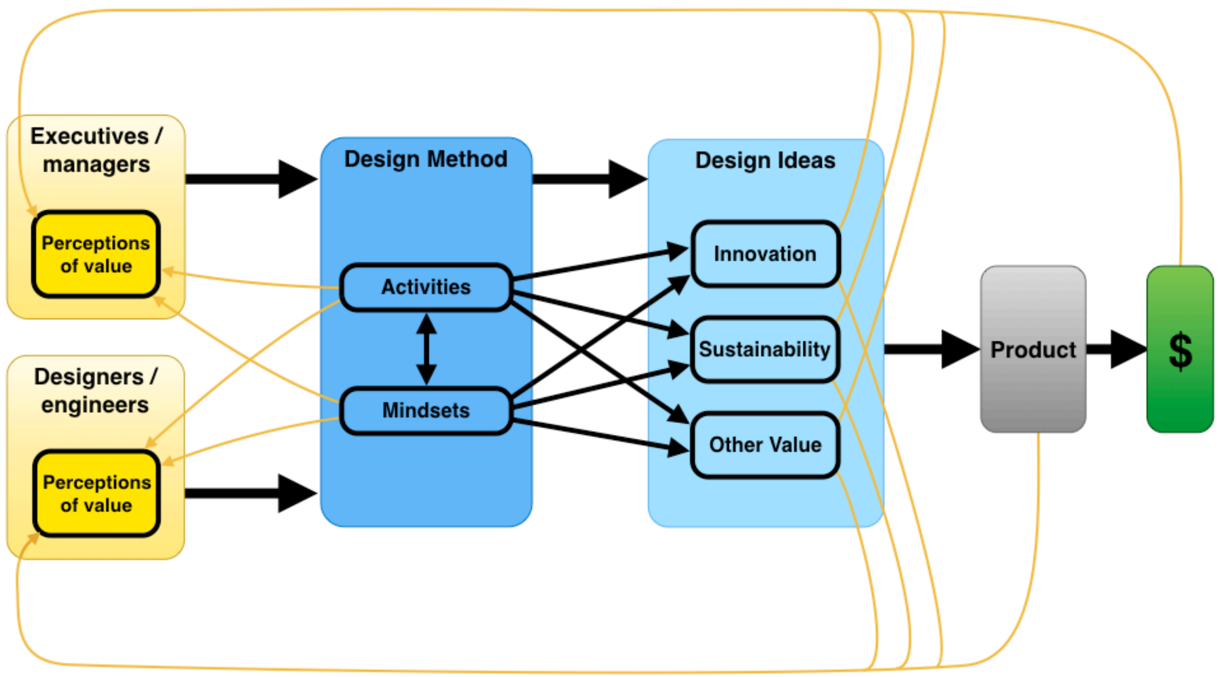

Figure 1.1 Conceptual model of the design process, with activities and mindsets within design methods driving design ideas, and with practitioners' perceptions of value.

Figure 1.1 shows the conceptual model used in this study. Designers / engineers and managers / executives (collectively referred to in this thesis as "practitioners") use a design method to produce design ideas; some of those ideas result in a final product, which is sold to create profits for the company. These practitioners have perceptions of what they value more or less in design practices. Design methods are comprised of activities and mindsets, each of which may have some effect on design ideas. Each design idea has some degree of innovation, sustainability, and other value (cost, quality, marketability, etc.) These are perceived by practitioners to have more or less value. Of course, the final product and its profits are perceived to have value as well, and the practitioners enacting different activities or considering different mindsets have direct perceptions of their value, also.

In addition to this literature review and conceptual overview, more detailed literature reviews appear in each subsequent chapter to provide greater depth specific to each portion of this study.

1.3. Scope of Work and Summary of Methods

This project attempted to answer four overarching research questions (RQs):

- RQ1. What activities & mindsets exist within sustainable design methods, and how do they depend on each other?
- RQ2. What do design teams value in design methods generally?
- RQ3. In these green design methods, which activities & mindsets drive sustainability, innovation, and other value for students?
- RQ4. In these green design methods, which activities & mindsets drive sustainability, innovation, and other value for professionals?

To answer these questions, several data sources and methods were used: For background and scoping, literature was reviewed and eighteen experienced professionals were interviewed (hereafter called "non-workshop" interviews, since they did not participate in workshops). Based on insights from these interviews and a literature review, fourteen design methods / guides / certifications / other practices were selected for analysis and comparison; multiple primary source documents were analyzed for each of these. Of these design practices, three sustainable design methods were selected for in-depth testing via workshops with students and professionals. Six workshops were performed for a total of 327 students, 262 of whom responded to surveys. Twenty-three workshops were performed for a total of 258 professional designers, engineers, managers, executives, and other jobs from over 30 different companies, 198 of whom responded to surveys; 26 were disqualified for being in non-product-related industries (e.g., architecture or software) or holding non-relevant job roles (e.g., marketing, sales, or operations), leaving 172 qualified respondents. This totaled 585 participants and 434 survey respondents. Data generated from each workshop included pre- and post-workshop surveys (both for students and professionals). For professionals, eight post-workshop interviews and ten followup interviews (three to eight months after workshops) were also performed, resulting in a total of 36 interviews. Videos of workshops were also recorded to assess levels of engagement (both for students and professionals), and photographs of workshop artifacts (post-it notes and whiteboards) were taken to quantify innovation and sustainability of ideas from workshops, but these were abandoned due to inconclusive results. All data sources used in the final study are shown in Figure 1.2.

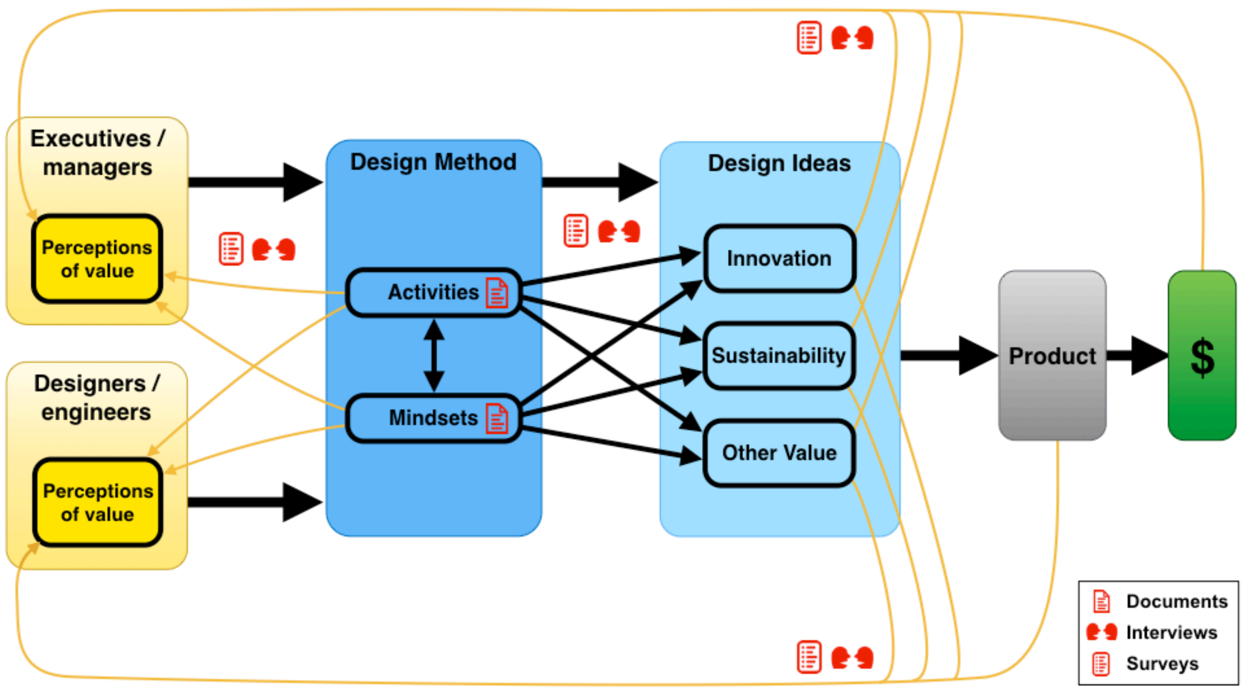

Figure 1.2 Data sources for research questions.

Figure 1.2 shows the conceptual model with data sources used to answer the four research questions. Design methods were taught in workshops (not labeled separately), resulting in design ideas. RQ1 was answered with primary source literature; RQ2 was answered with non-workshop interviews, post-workshop interviews, and pre-workshop surveys; RQ3 was answered primarily with post-workshop surveys, validated through final reports; RQ4 was primarily answered with post-workshop surveys, validated through post-workshop interviews and followup interviews. A more detailed list of questions, data sources, analysis methods, and validation is listed in Table 1.1.

Table 1.1 shows the entire project research plan. The four overarching questions are the four chapters of this dissertation; each is comprised of several more specific "selection questions" which were directly answered with specific data sources analyzed in specific ways, as listed. Then the validity and reliability of analysis were checked in various ways, as explained. The final column lists whether the analysis and validation were quantitative or qualitative.

Detailed discussions of this plan's different components appear in subsequent chapters, including more detailed literature reviews, descriptions of methods, resulting data and interpretations, and conclusions. To summarize, the chapters are as follows:

Research Questions	Selection Questions	Literature Review	Pre-Survey - Student	Post-Survey - Student	Final Reports - Student	Interview - Pro	Pre-Survey - Pro	Post-Survey - Pro	Post-Interview - Pro	Followup Interview - Pro	Kinds of Analyses	Validity & Reliability	Qual/ Quant
		Data Collection Methods											
RQ1. What activities & mindsets exist within sustainable design methods, and how do they depend on each other?	What kinds of activities & mindsets exist within each design method?	X									• Code literature on methods for component activities & mindsets • Classify activities & mindsets	• 2 people code; calculate Kappa	Qual
	How much do activities & mindsets differ or overlap from method to method?	X									• Chart overlap / difference of activities & mindsets between methods	N/A (result of coding)	Qual
	Are some activities & mindsets required or helpful for other activities & mindsets?	X									• Map process-dependency of activities & mindsets in each design method	N/A (result of coding)	Qual
	What design methods are designers, engineers, and managers likely to value more?	X									• Form hypotheses based on activity & mindset categories	• Test empirically in RQ2, RQ3	Qual
RQ2. What do design teams value in design methods generally?	What general design methods / activities mindsets do practitioners value?		X			X	X		X		• Interviews & Pre-surveys: Count how many people say they valued a method / activity / mindset.	• 2 people code for reliability • Compare interviews to pre-surveys	Quant
	Why are they valued? Why are they criticized?		X			X	X		X		• Interviews & Pre-surveys: Code & cluster why people say they value a method / activity / mindset.	• 2 people code for reliability • Compare interviews to pre-surveys	Qual
	How do they measure innovation?	X				X			X		• Interviews: how do they measure innovation?	• 2 people code for reliability	Qual
	Who can best drive sustainability in your company, and how?					X			X	X	• Interviews: Code & cluster who people say can drive sustainability, and how.	• 2 people code for reliability	Qual
RQ3. In these green design methods, which activities & mindsets drive sustainability, innovation, and other value for students?	Which activities & mindsets in these design methods are generally valued more than			X	X						• Post-surveys: Count how many people say they valued an activity / mindset.	• 2 people code for reliability • Compare surveys to final reports	Quant
	Why are they valued?			X	X						• Post-surveys: Code & cluster why people say they valued an activity / mindset.	• 2 people code for reliability • Compare surveys to final reports	Qual
	Which activities & mindsets in these design methods drive sustainability more than others?			X	X						• Post-surveys: Count how many people say an activity / mindset related to sustainability	• 2 people code for reliability • Compare surveys to final reports	Quant
	Why / how do they do so?			X	X						• Post-surveys: Code & cluster why people say an activity / mindset related to sustainability	• 2 people code for reliability • Compare surveys to final reports	Qual
	Which activities & mindsets in these design methods drive innovation more than others?			X	X						• Post-surveys: Count how many people say an activity / mindset related to innovation	• 2 people code for reliability • Compare surveys to final reports	Quant
	Why / how do they do so?			X	X						• Post-surveys: Code & cluster why people say an activity / mindset related to innovation	• 2 people code for reliability • Compare surveys to final reports	Qual
	Are different sustainable design methods beneficial or detrimental to product cost, quality, and other business factors?		X	X							• Pre-surveys: Checklist of perceptions on how sustainability generally affects the design process & outcomes. • Post-surveys: Checklist of perceptions on how that design method affects the design process & outcomes.	• 2 people code for reliability	Quant
RQ4. In these green design methods, which activities & mindsets drive sustainability, innovation, and other value for professionals?	Which activities & mindsets in these design methods are generally valued more than							X	X	X	• Post-surveys: Count how many people say they valued an activity / mindset.	• 2 people code for reliability • Respondent validation in interviews	Quant
	Why are they valued?							X	X	X	• Post-surveys: Code & cluster why people say they valued an activity / mindset.	• 2 people code for reliability • Respondent validation in interviews	Qual
	Which activities & mindsets in these design methods drive sustainability more than others?							X	X	X	• Post-surveys: Count how many people say an activity / mindset related to sustainability	• 2 people code for reliability • Respondent validation in interviews	Quant
	Why / how do they do so?							X	X	X	• Post-surveys: Code & cluster why people say an activity / mindset related to sustainability	• 2 people code for reliability • Respondent validation in interviews	Qual
	Which activities & mindsets in these design methods drive innovation more than others?							X	X	X	• Post-surveys: Count how many people say an activity / mindset related to innovation	• 2 people code for reliability • Respondent validation in interviews	Quant
	Why / how do they do so?							X	X	X	• Post-surveys: Code & cluster why people say an activity / mindset related to innovation	• 2 people code for reliability • Respondent validation in interviews	Qual
	Are different sustainable design methods beneficial or detrimental to product cost, quality, and other business factors?						X	X		X	• Pre-surveys: Checklist of perceptions on how sustainability generally affects the design process & outcomes. • Post-surveys: Checklist of perceptions on how that design method affects the design process & outcomes.	• 2 people code for reliability	Quant
	Did participants continue using any activities / mindsets / methods after workshops?									X	• Followup interview: Did they continue using any activities / mindsets / methods after workshops?	• 2 people code for reliability	Quant
	Did ideas from these design methods become released products?									X	• Followup interview: any product ideas from workshop continue in development? Actions participants took to pursue ideas.	• 2 people code for reliability	Quant

Table 1.1 Summary of research questions, data sources, and analysis methods. "Pro" = professional participants, "Quant" = quantitative analysis, "Qual" = qualitative analysis.

Chapter 2, “Characterizing Activities And Mindsets to Hypothesize Recommendations For Sustainable Design Practices“ deconstructs fourteen design methods, guides, certifications, and other practices into their component activities and mindsets. It categorizes these activities and mindsets, and compares the to hypothesize what sustainable design practices designers, engineers, and managers would each find most useful; it also hypothesizes what sustainable design practices might be best suited for what stage in the design process. However, it does not speculate on which activities or mindsets practitioners find most valuable.

Chapter 3, “What Practices Do Design Professionals Generally Value for Innovation and Sustainability?“ describes 42 interviews with professional designers, engineers, and managers, asking them what sustainable design methods they have used and why, what standard design methods they have used and why, how they measure or define innovation, and what they value in design methods generally. Of these, 27 interviews were with professionals not participating in workshops; these established broader context for the study, helped choose the design methods tested in workshops (chapters 4, 5, and 6), and helped determine the survey questions for workshop participants. Seven were post-workshop interviews to validate and complement survey data from workshop participants. Finally, ten were followup interviews several months after workshops to investigate lasting effects. For all interviews, quantitative and qualitative analysis found what activities and mindsets were most valued and most criticized, whether they were valued for sustainability or innovation or both, and why.

Chapter 4, “Workshop Procedures“ lists the methods for delivering workshops on the three sustainable design methods studied in detail: The Natural Step, Whole System Mapping, and Biomimicry. The chapter lists all activities and mindsets taught in each workshop. The same workshops were taught for students and professionals, with some differences due to workshop duration. Results of the workshops are described in chapters 5 and 6.

Chapter 5, “Effective Sustainable Design Methods: Where Do Students Find Value and Innovation?“ describes the investigation into what students most value in design methods. Six workshops in three sustainable design methods (The Natural Step, Whole System Mapping, and Biomimicry) were performed, with survey feedback from 262 UC Berkeley students. Quantitative and qualitative analysis found what activities and mindsets were most valued and most criticized, whether they were valued for sustainability or innovation or both, and why. Results were also broken down by demographics (engineering students versus business students, gender, and industry sector) to see if different groups valued different practices.

Chapter 6, “Effective Sustainable Design Methods: Where Do Professionals Find Value and Innovation?“ describes the second investigation into what professionals most value in design methods. Twenty-three workshops in the three design methods were performed, with survey feedback from 172 professional designers, engineers, and managers. Quantitative and qualitative analysis found what activities and mindsets were most valued and most criticized, whether they were valued for sustainability or innovation or both, and why. Results were also broken down by demographics (designer / engineer / manager, company type, company size, gender, industry sector, and workshop duration) to see if different groups valued different practices.

Chapter 7, “Conclusions and Recommendations“ summarizes the findings from all chapters, lists overall conclusions based on the combination of all findings, and suggests directions for future research.

1.3.1. Validity, Reliability, and Generalizability

The research methodology of workshops, surveys, and interviews followed Campbell and Stanley's “equivalent materials samples design“ in order to maximize internal validity, minimizing most common causes of invalidity such as maturation, testing, history, instrumentation, regression to the mean, selection, and interactions thereof [Campbell et al., 1963]. Survey and interview questions and structure were designed according to Krosnick and Presser's recommendations for open vs. closed questions, ordering, and other factors to improve validity and reliability [Krosnick and Presser, 2010]. In addition, validity of qualitative analyses was checked by triangulating data from pre- and post-workshop surveys, pre- and post-workshop interviews (for professionals only), non-workshop-related interviews (for professionals only), and final project reports (for students only) against each other. This triangulation viewed the problem through six different sets of data, including before and after interventions. In addition, attempts were made to check validity of qualitative analyses by gathering “rich data“ (video recordings of workshops and photographs of workshop artifacts such as post-it notes and whiteboards), though their analysis results were not conclusive, so they are not described. However, followup interviews (for professionals only) three to eight months after workshops asked participants to affirm or deny tentative conclusions, providing respondent validation.

As Maxwell argued [Maxwell, 2012], there is no boilerplate method to guarantee a study's validity; there are only ways to anticipate weak points and amass evidence to prevent them from undermining the study. The primary threats to this study's validity were reactivity, bias, artificiality, and lack of generalizability (both internal and external). These were addressed as follows:

Reactivity includes ordering effects, reactions to workshops, and reactions to interview / survey question framing. It was avoided by several means: triangulation (described above) avoided reactivity to questions by framing questions differently in surveys and interviews. Triangulation avoided reactivity to workshops by comparing workshop interviewees to non-workshop interviewees. The interpretation and clustering phases of analyses included searching for discrepancies or negative cases. Finally, ordering effects were minimized by running workshops in different orders for both students and professionals. For professionals, companies were also recommended to wait one month or more between workshops so the previous workshop was no longer freshly remembered, or have different participants from the company in different workshops. There were two cases where this was not achieved, due to company scheduling availability and participant interest, but it was achieved in the other 21 workshops.

Bias was avoided by the multiple coders described above, inductive methods, and by the unit of analysis. A “horse race“ comparison of which design method practitioners found most valuable might be prone to bias, as the principal investigator both delivered all workshops and developed one of the design methods studied (Whole System Mapping). Despite attempts to be objective, he might perform that workshop more enthusiastically or expertly than the others. Selecting activities / mindsets as the unit of analysis instead of whole design methods allowed the study to avoid this bias by finding what participants value in each design method. This is the process of user-testing prototypes, where there is no advantage to preferring one prototype against another, as none will be the final product; instead, the best product is achieved by finding the best and worst characteristics of all prototypes [Ulrich and Eppinger, 1995]. In addition to this, activities and mindsets were identified and counted using an inductive method of analysis based on Harry's procedure for grounded theory [Harry et al., 2005], establishing a six-step bottom-up approach to coding to minimize bias. As mentioned above, all coding was also independently performed by a research assistant, with Cohen's Kappa calculated to determine acceptable reliability.

Artificiality of the study was minimized by several means: First, by studying professional teams as well as students. Second, by workshopping real products wherever possible instead of artificially created exercises (though four company teams did opt for products whose design was already completed, to avoid intellectual property risk). Third, for professionals, through followup interviews several months after workshops, asking if participants used anything from the design methods in their actual professional practice, and by comparing against non-workshop interviews, since those participants experienced no artificial intervention.

Internal generalizability / reliability were ensured by gathering significant amounts of data, using a fine-grained unit of analysis, and gathering data from relevant participants. Sufficient quantities of data per activity / mindset were ensured by the large number of workshops: each workshop type received 48 – 96 professional respondents and 89 – 134 student respondents. This is two to twenty times as many datapoints as used in many qualitative research studies [Chi, 1997] [Barron, 2003] [Oehlberg et al., 2011] [Steffe and Thompson, 2000]. Also, as mentioned earlier, most companies participated in two workshops and each workshop was performed for four or more companies. The fine-grained unit of analysis provides data on over 60 activities and mindsets, rather than the three design methods, which also provides more datapoints for finding trends. The relevant participants were company designers, engineers, and team leaders (managers / executives), because they are the people who design products in industry; the mechanical engineering and business student participants were also indirectly relevant, as many of them will go on to become engineers and managers in product development teams.

External generalizability will be limited, but was maximized by choosing a broad range of company types to participate. Workshop participants included both manufacturers and design consultancies in several industry sectors, including consumer electronics, furniture, housewares, and apparel. Interviewees included individuals from these industries as well as medical devices, automotive, food, telecommunications, aerospace, packaging, and other industries. However, architecture and software were not included; any participants from these industries attending workshops at conferences were disqualified (their survey results were not used), because these industries were assumed to differ too much in design practices from general product design. Many design consultancies (such as IDEO, Lunar, frog, Fuseproject, and more) consider their design methods applicable to such sectors as well, so future researchers could broaden the scope of study to include them.

Reliability was tested by two researchers independently coding all data of all types for all analyses. Intercoder agreement was computed using Cohen's Kappa statistical method [Cohen, 1960]. Most results scored over .80 with no adjustment. When average scores for a group of participants (e.g., post-workshop surveys from students in ME110 Spring 2015) were less than .80, researchers examined and discussed discrepancies until they agreed on new coding rubrics and/or category redefinitions to improve agreement up to Landis's “almost perfect“ level [Landis and Koch, 1977].