

Robust Design Review Conversations

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***Abstract:** Design reviews and executive conversations at the point of strategic decision-making share an important outcome: they both result in the (nearly) irrevocable allocation of resources to pursue a design concept or strategic option. Our study aims to contribute to the strategic decision-making scholarship by investigating the robustness of these conversations. We define a robust design review conversation as one in which the participants discuss evidence in favor of and against the option and at the same time propose new hypotheses to explain or resolve the evidence in favor of and against the option, hypotheses that can eventually be tested. We describe this second process as generative sensing. Whereas the first process is likely to rely on deductive reasoning from established rules to a definitive conclusion, the second is likely to rely on abductive reasoning, a form of reasoning that generates new hypotheses that are candidate parsimonious explanations for the evidence. We analyze and compare the design review conversations from a junior-level undergraduate course in industrial design and an entrepreneurship course. We find more instances of generative sensing in the industrial design review sessions than in the entrepreneurship project presentations. We believe that generative sensing serves three instrumental purposes: to resolve problems; to provide signals on option quality; and, to test the commitment to the present design concept.*

Keywords: strategic decision making; generative sensing; design evaluation

1. Background

The decision to take a product from its conceptual design into detailed design has properties of strategic decisions as defined in the strategic management field. The decision irreversibly commits a significant investment of resources (high degree of commitment) toward delivering or expanding a new product or service (changes the scope of the firm) (Shivakumar, 2014). The quality of the decision significantly affects the performance of the company taking the decision. In design, it has been suggested that the quality of early design decisions largely determines downstream costs (Ulrich & Pearson, 1993). While it is disputed whether design decisions *per se* determine 70% of product costs (Barton, Love, & Taylor, 2001) or 80% of manufacturing costs (Ulrich & Pearson, 1993), or whatever other percentage of downstream costs, it is not contested

that the quality of the decision has a significant effect on the downstream costs (Barton & Love, 2000).

Researchers and scholars in engineering design and new product development have, as such, motivated their research in decision-based design as having relevance to the strategic nature of these decisions. To improve the quality of design decisions, scholars of design decision making have tended to focus on how to take a decision for a range of tasks consistently faced in new product design and development (Krishnan & Ulrich, 2001). Perhaps the most important decision taken during design is concept selection, the analysis and evaluation of alternative concepts, leading to the selection or consolidation of one or more concepts for further development. A range of normative decision-making tools and methods for concept selection exist, including concept screening (Ulrich & Eppinger, 2004), pair-wise comparison charts (Dym, Wood, & Scott, 2002), concept scoring matrices (Frey et al., 2009; Pugh, 1981), multi attribute utility analysis (Scott & Antonsson, 1998; Thurston, 1991), and Pareto dominance (Malak & Paredis, 2010). As a consequence, there has been a very robust and long-standing debate surrounding the decision method to use once a discrete set of alternatives is known (Frey et al., 2009; Hazelrigg, 2010; Reich, 2010; Scott & Antonsson, 1999) and the type of design decisions for which the axioms of decision theory ought to be applied (Hazelrigg, 1998; Lewis, Chen, & Schmidt, 2006; Thurston, 2001).

Lost in this debate, though, is the quality of the decision making process itself. Taken together, a broad body of research in the strategic management literature points to the conclusion that decision processes matter to the performance of the project first and to the performance of the firm second. More specifically, several works have shown that the rationality of a decision, often measured in terms of the extent to which the analysis of the decision is comprehensive, has a positive impact on the extent to which the implementation of the decision meets the expectations at the time of the decision, but the use of political tactics has a negative one (Dean & Sharfman, 1996; Elbanna & Child, 2007). Similarly, it has been found that decision making processes matter for a firm's performance (Fredrickson & Mitchell, 1984; Papadakis & Barwise, 2002).

More recently, two studies have pointed toward the importance of conversations over numbers and financial analysis in decision-making. First, in a study of new-to-the-firm products, resistance was won by using micropolitical strategies. This happened by building a coalition of supporters but especially by framing the product in terms of the firm's existing products, strategies, and competitive thrusts (Sethi, Iqbal, & Sethi, 2012).

Second, a large sample study of strategic decisions has highlighted how strategic conversations are substantially more important than the (financial) analysis of a decision in shaping the outcomes of such decisions (Garbuio & Lovallo, 2011; Lovallo & Sibony, 2010). In this study, it was "how" the executives talked about the decision and its underlying assumptions that had an impact on whether expectations in terms of market share or profitability were met, not "what" financial analysis was performed. Also, overconfidence (Kahneman & Lovallo, 1993) and heuristics that are subject to framing effects (Gilovich, Griffin, & Kahneman, 2002) and the manner in which the alternatives are presented to decision-makers (choice architecture) (Thaler & Sunstein, 2008) all point toward cognitive issues associated with decision-making (Garbuio, Lovallo, & Ketencioglu, 2013).

Building on research on the quality of dialogue in design in accomplishing actions and practices of design (Luck, 2009) to enable the emergence of tangible goods (Dong, 2007; Oak, 2011), this study aims to contribute to the decision making scholarship in design by investigating the cognitive foundations of strategic design review conversations. We focus on the situation of the review of design concepts presented throughout a junior-level (third-year) undergraduate industrial design course and the final presentations of an entrepreneurship course at a Public University in the United States. The conversations in the industrial design course contain discussions about multiple design concepts, which can lead to the abandonment or further development of design concepts until a final concept is chosen. In contrast, the entrepreneurship presentations communicate a single project and are representative of the type of presentation to an executive committee tasked with making a resource allocation decision (i.e., a go/no-go decision). The research we perform addresses the quality of these conversations.

2. Theoretical Frameworks

The evaluation of a design concept is a key part of the design process. By evaluation, we mean assessing the merits and shortcomings of proposed design concepts (e.g., non-fully elaborated ideas for new products), which takes place throughout the design process until a single, fully elaborated candidate design is selected as the final option. To assist designers in filtering ideas, researchers have proposed metrics to quantify the creativity of a design concept (Nelson, Wilson, Rosen, & Yen, 2009; Oman, Tumer, Wood, & Seepersad, 2013; Shah, Smith, & Vargas-Hernandez, 2003; Verhaegen, Vandevenne, Peeters, & Duflou, 2013) and a social process to achieve agreement on the degree of creativity of an idea (Amabile, 1983) or consensus on the decision (Yang, 2010). The problem we see is that these methods call for deductive reasoning, such as in quantifying novelty by comparing an idea to a universe of ideas (Maher, 2010; Shah et al., 2003). Empirical research in industry for concept evaluations also describe decision-makers as tending to apply variables amenable to deductive analysis including product timing, staffing, and platform when evaluating innovative projects (Krishnan & Ulrich, 2001; van Riel, Semeijn, Hammedi, & Henseler, 2011). Even in the situations when the concept is in its early phases, design concept evaluation techniques likewise employ highly deductive analysis requiring a substantial amount of criteria for analysis (Ulrich & Eppinger, 2004). Even when the concept is a new invention to the world (Udell, 1989), decision-making methods promote deductive reasoning to prove or disprove premises established by precedence. Deductive reasoning can potentially indoctrinate pattern recognition biases and decision myopia (Lovallo & Sibony, 2010).

The second problem is that the evaluation is grounded in theories about normative decision-making methods. These methods propose a series of hurdles for the decision-maker. First, all of the methods require the decision-makers to express their preference (subjective utility) toward alternatives. Utility-theory based methods additionally require the decision-maker to model uncertainty in their preferences in a quantitative manner. Explicit preference information is sometimes quantitatively available, but often it is not. In design, this is particularly challenging in the early phases of concept development, resulting in the situation of engineers not knowing how to apply methods requiring quantitative preference information correctly due to the challenges of defining the utility of attributes (López-Mesa & Bylund, 2011). Second, when the decision occurs within a group, it is not possible to construct a single group utility function,

because the group decision is dependent upon the voting rule and the voting procedure (Arrow, 1963; Scott & Antonsson, 1999).

If the purpose of design evaluations were to evaluate concepts only as presented with no further elaboration possible, then these types of metrics make sense. The accepted practice is that design evaluation *per se* in the choice phase (i.e., when decision makers are presented with a discrete set of options) should only examine the merits of options. However, we believe that design evaluations should *always* entail both the evaluation of the quality of the design concept and be “forward looking” for “what might be”.

Companies that are successful at innovation know the importance of discussing the assumptions behind evidence rather than simply using them at face value. Govindarajan and Trimble (2010) conducted a ten-year study into innovation within established companies that provided insights into the importance of what they call “conversational modeling” as opposed to mathematical modeling. In the companies they studied, effective decisions were based on extensive discussion about the assumptions – the hypotheses of record – that were sometimes communicated through simple pencil-and-paper sketches. Successful decisions were more likely to be the result of improving conversations rather than analysis. For example, even the tools that are used to support the conversation were found to be of importance. Conversations cannot be based on spreadsheets. In their words, “the spreadsheet is an exceptionally poor tool for documenting and sharing the hypothesis of record. [...] The thinking underlying the calculations is what matter most, but is buried in equations that are difficult to review and interpret.” (Govindarajan & Trimble, 2010, p. 126) In fact, whereas ongoing operations are only marginally about unknowns, in strategic initiatives only a small percentage of what lies ahead is known. If your conversation is only about the results of the data, you risk leaving out a large chunk of what matters. Unfortunately, “the most critical information in the plan – the assumptions underlying the predictions – are often poorly communicated, poorly understood, and quickly forgotten” (Govindarajan & Trimble, 2010, p. 111).

To deliberate about what lies ahead, though, when the available evidence is likely to be conflicting or inconclusive, decision makers must attempt to make sense of the evidence obtained, not simply make use of the evidence as it presents itself. Kolko (2010) has argued that making sense of ambiguous evidence is a key part of the reasoning that designers apply, a process he attributes to abductive reasoning. Thus, rather than the evaluation of a design concept being ‘static’ based only on existing evidence, we propose a dynamic model. We hypothesize that a robust design review conversation should consist of at least two dimensions. The first is strategic analysis. We define strategic analysis in the design context as the extent to which decision makers use evidence to evaluate design quality based upon *a priori* design criteria such as the requirements. When we refer to evidence, we mean propositions that justify a belief; propositions may include *inter alia* observable properties of the concept, arguments based upon belief or experience, or secondary data (such as consumer testing).

We hypothesize that the second core dimension of a robust design review conversation is the quality of generative sensing. We define generative sensing as the process of creating new hypotheses to explain or resolve the evidence in favor of or against a design concept, evidence that was itself generated from an evaluation of the design concept. We differentiate this form of

sensing to organizational sensemaking, which is retrospective and social with an emphasis on the social processes whereby organizations develop a way of ‘seeing things’ (Weick, 1995) or framing (Dorst, 2011). In the context of design evaluation, generative sensing entails inferences to explain the evaluation. These inferences may provide resolutions to problems identified by the evaluation when the evaluation is adverse. In contrast, a positive evaluation may spur the consideration of potential negative future possibilities that would undermine the basis of the evaluation in order to test the robustness of the evaluation.

Generative sensing based upon the output of the evaluation of the design concept can lead to new knowledge that changes the designer’s view of the design concept, resulting in a reframing of the problem itself (Dorst & Cross, 2001). In design, making the leap from the evaluation of a design concept to a final design concept is not solely about testing the merits of the design concept as a *fait accompli*; rather, it is about generating a series of tests of the design concept until an appropriate concept is identified. At each step, the designer attempts to make sense of the synthesis of new evidence introduced as a result of the conclusion from the evaluation.

Our concept of generative sensing shares some ideas with the concept of the primary generator (Darke, 1979). A primary generator is a conjecture, or better stated, a design strategy based upon establishing a broad set of objectives as the basis for establishing potential solutions. These objectives, which do not satisfy all constraints, provide a “way in to the problem” (Darke, 1979, p. 38). Generative sensing entails producing hypotheses that may resolve (or further expand) issues encountered in the evaluation of a design concept. Thus, rather than a “way in to the problem”, generative sensing can be seen as creating alternative “ways through the problem”.

The cognitive foundation of generative sensing is abductive reasoning. The concept of abduction in design is philosophically very powerful as it introduces a mechanism of discovery through a form of logical reasoning. Scholars have theorized that the relevant form of abductive reasoning in design is innovative abduction. Innovative abduction produces an explanation (the design concept) for the desired phenomenon, the function, and, in turn an explanation (the form) for the design concept (Kroll & Koskela, 2014; Roozenburg, 1993). As Dorst writes, designers must engage in a form of reasoning “to figure out ‘what’ to create, while there is no known or chosen’ working principle’ that we can trust to lead to the aspired value” (Dorst, 2011, p. 524). The term value is not restricted to economic or financial value, but, rather, any values to which the designer aspires (Friedman & Kahn Jr., 2003; Le Dantec & Do, 2009; Lloyd, 2009). In other words, abductive reasoning in design generates hypotheses that, if true, would explain the form of the proposed product and its mode of operation given a desired value (Roozenburg, 1993). Design theory scholars propose that the major premise that abductive reasoning must infer is the rule that connects a form to its function within an operating environment (Zeng & Cheng, 1991). This logical reasoning from function to form appears to refer to Sullivan’s widely cited credo that “form ever follows function” (Sullivan, 1896) although scholars of abductive reasoning in design do not refer to Sullivan explicitly. If function or value is intentional, then innovative abduction in design is about inferring a form that achieves an intended purpose. The purpose may not necessarily be utilitarian or performative.

Roozenburg (1993) introduces the following notation to describe innovative abduction:

q	a given fact (function or value): q

$p \Rightarrow q$	a rule to be inferred first: IF p THEN q
p	the conclusion: p

Kroll and Koskela (2014) extend the model of abduction proposed by Roozenburg (1993) and Dorst (2011) into a two-step recursive inference of the innovative abduction: the first step involves abduction of a concept given a function and the second step involves abduction of a form given the concept inferred from the previous step.

q	a given fact: <i>function</i>

$p \Rightarrow q$	first conclusion: IF <i>concept</i> THEN <i>function</i>
p	second conclusion: <i>concept</i>
q	a given fact: <i>concept</i>

$p \Rightarrow q$	first conclusion: IF <i>form</i> THEN <i>concept</i>
p	second conclusion: <i>form</i>

In the evaluation of a design concept, we propose that the logical process of design does not (should not) arbitrarily stop. In other words, the participants should continue to propose hypotheses that infer the link between function and form in a recursive manner. Each inference is only a partial result to the problem, the depth of which depends upon the complexity of the problem and the number of sub-problems to be resolved (Zeng & Cheng, 1991). Thus, inferring the working principle (concept), which is comprised of mode of operation and way of use (Roozenburg, 1993), can entail multiple recursive inferences.

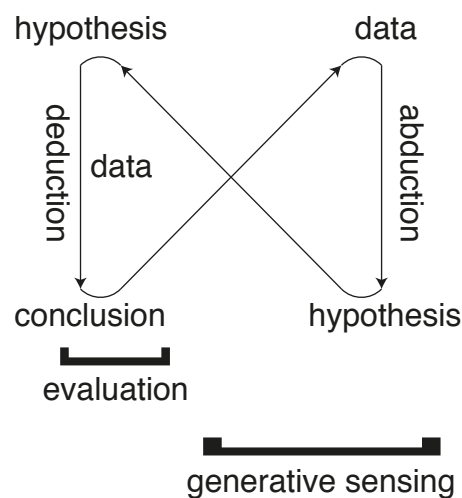


Figure 1. Generative sensing in robust design review conversations

The model of robust design review conversations we propose is therefore comprised of two components: deductive analysis of available data based upon established criteria and generative sensing of the current evaluation, which leads to new testable hypotheses that can then be tested using deductive analysis. The model is depicted in the following diagram, Figure 1:

In summary, within the confines of a design problem, we argue that a robust design review conversation should analyze and evaluate the data at hand and make sense of the evaluation through testable hypotheses that best explain the evidence in favor of or against the design concept. These hypotheses should then be tested over the course of the design project, if the decision takes place within the design phase, or during post-launch review (Cooper, 2014; Cooper, Edgett, & Kleinschmidt, 2002).

In this study, we investigate both dimensions of robust design review conversations.

3. Methodology

We believe that the core components of robust design conversations are the extent to which the decision makers use evidence and generate testable hypotheses about the evidence in favor or against the design concept. We analyzed the design review conversations in a junior (third-year) industrial design course and an entrepreneurship course obtained from a database of design review conversations recorded for the Design Thinking Research Symposium (DTRS) 10 (Adams & Siddiqui, 2013). The selection of these polar types is intended to make the two types of reasoning processes, deductive and abductive, more observable (Eisenhardt, 1989). The entrepreneurship course project presentations should emphasize ‘hard’ evidence conducive to managerial decision-making. Pitches to investors for an entrepreneurial business opportunity emphasize verifiable evidence such as marketplace acceptance and the size and accessibility of the market because the investment decision is determined by an appraisal of this evidence (Clark, 2008). The context of the presentation limits the amount of conversation that can occur, except for a brief question and answer session at the end of the presentation. In contrast the industrial design context is more likely to contain elements of “design thinking”, a core element of which is abductive reasoning (Dorst, 2011), and thus more of the second component of robust design review conversations, generative sensing. The industrial design project brief of introducing a new seating concept offers scope for the students to explore possibilities rather than to solve a defined problem. For the industrial design course, we analyzed transcripts from the initial design review to the client review and the final review. We aimed to analyze transcripts for which there was continuity across all the review sessions for the same industrial design student. We analyzed 11 transcripts containing about 2 hours of dialog from the junior industrial design course and all 6 presentations from the entrepreneurship course, each lasting 10 to 15 minutes.

To code the transcripts, we build upon the method employed in DTRS7 dataset (McDonnell & Lloyd, 2009) to code judgment in design conversations (Dong, Kleinsmann, & Valkenburg, 2009) and a coding scheme for forms of logical reasoning during design review conversations at the point of deciding to pursue or reject alternatives (Dong, Lovallo, & Mounarath, Accepted 24 October 2014).

To code the extent to which decision makers evaluate options based upon data, instances of appraisals of a product were identified. Yilmaz and Daly (2014) coded these types of evaluations as feedback on artifact quality. We analyzed the transcripts for the following types of evaluation of design concept quality (Kelley & Littman, 2001):

Table 1. Criteria for coding discussions of design quality

Code	Criteria	Example	Source
Customer acceptance (CA)	Appraises or questions issues associated with the human dimension of the product including utility, user experience, usability, emotional appeal, meaning, value, etc.	But I think <i>this is a great idea</i> ‘cause <i>that’s a great utility</i> , ‘cause <i>this is a real negative wasted amount of space</i> . <i>I think that’s a good idea</i> .	[Gary] 1-ID-jr-FirstReview-Lynn
Technical feasibility (TF)	Appraises or questions issues associated with the implementation and servicing of the product including manufacturability, environmental impact, disposal, in-use servicing, etc.	You know that spiral if you really, really looked and <i>this is very difficult to do in foam</i> , <i>it’s very almost impossible</i> so that’s something like the chair like form you can bring that in and fit it to these dimensions. <i>It’s very difficult to fit in foam this first one</i> .	[Gary] 3-ID-jr-Client Review Addison
Economic feasibility (EF)	Appraises or questions microeconomic issues associated with the product including price acceptability to target market, appropriate market size, existing competitor products, etc.	I just, <i>I just don’t know how we would make it</i> , <i>make it - affordable</i> and it’s uh.	[Darren] 3-ID-jr-ClientReview-Lynn-Todd

To analyze for abductive reasoning, which we argue is the cognitive foundation of generative sensing, we developed a coding scheme that is grounded in the theories of abductive reasoning in design. To them, we make two important extensions. Roozenburg (1993) combines mode of operation and way of use together. It is preferable to distinguish them because the way of use (mode of user operation) is a non-trivial inference. The mode of user operation is the ‘interaction design’, which is non-trivial, especially since innovative designs tend to improve upon user interaction (Saunders, Seepersad, & Holtta-Otto, 2011). The way of use is contingent both upon the mode of operation and on form. For example, the touch screen interface on your cell phone depends upon capacitive sensing and the flat glass form of the phone. Consistent with functional modeling and the functional basis (Stone & Wood, 2000), though, the way of use is a form of human energy that is transferred to the object so as to actuate a function. Thus, we believe that

mode of user operation so as to enact its mode of operation should be explicitly included as a sub-problem to be resolved through abductive inference.

We describe the mode of user operation in the following abductive inference:

q	a given fact: <i>function</i>

$p \Rightarrow q$	first conclusion: IF <i>mode of operation</i> THEN <i>function</i>
p	second conclusion: <i>mode of operation</i>
q	a given fact: <i>mode of operation</i>

$p \Rightarrow q$	first conclusion: IF <i>mode of user operation</i> THEN <i>mode of operation</i>
p	second conclusion: <i>mode of user operation</i>

Then, the next abduction could be to infer the form that enables the mode of user operation, such as a form that has the desired, intended affordance.

Previously, models of abductive inference in design linked reasoning from function to form only without consideration that it is also possible to situate the concept in a different context, which changes the interpretation of the function, or what Gero and Kannengiesser (2004) describe as type-3 reformulation in the situated function-behaviour-structure (FBS) framework. Thus, a situation exists wherein a designer infers a new context of use, at which point the designer can reason toward a new function not previously envisaged:

q	a given fact: <i>concept</i>

$p \Rightarrow q$	first conclusion: IF <i>context of use</i> THEN <i>concept</i>
p	second conclusion: <i>context of use</i>
q	a given fact: <i>context of use</i>

$p \Rightarrow q$	first conclusion: IF <i>function</i> THEN <i>context of use</i>
p	second conclusion: <i>function</i>

The change in context-of-use for the microsphere adhesive invented by 3M is a classic example of this type of abductive reasoning. Upon changing context-of-use of the adhesive to office stationery, a new function for the adhesive could be inferred – temporarily hold paper notes to surfaces.

To code for abductive reasoning associated with generative sensing, we use the criteria in Table 2. The first two codes, AS and AB, relate to the inference of a form and mode of operation as previously canvassed by Roozenburg (1993) and Dorst (2011), and the third code relates to the inference of a concept as canvassed by Kroll and Koskela (2014). The AU code relates to an inference about the mode of user operation, which is the mode of operation from the perspective of the individual who interacts with the object. The final code, AC, refers to an inference about a new context of use. We show the corresponding abductive logic in the notation described by Kroll and Koskela (2014) using example excerpts from the transcripts. Where more than one

abductive inference is shown, then the excerpt displays a recursive abductive inference (Zeng & Cheng, 1991), generally from function to concept to form as described by Kroll and Koskela (2014) with the variations described previously. We note that these are not necessarily complete examples of innovative abduction in design, that is, abduction from function to concept to form. The coding captures the participants in the process of abductive inference from the function to form, but some of their reasoning is not explicitly made available to us. The excerpts may represent only one of the recursive loops (Zeng & Cheng, 1991) that would be involved in the logical reasoning.

Table 2. Criteria for Coding Abductive Reasoning

Reasoning Frame	Criterion	Example	Source
Abductive (AS)	Modifying or introducing a new form for the concept	So what you have here it shows them sagged but if there was some sort of interconnection where you could actually pull that out and turn it into chair or -	[Max] Client Review – Todd
	q a given function: <i>connect multiple chairs</i> ----- $p \Rightarrow q$ first conclusion: IF <i>you could pull that out</i> THEN <i>connect multiple chairs</i> p second conclusion: <i>you could pull that out</i> q a given concept: <i>you could pull that out</i> ----- $p \Rightarrow q$ first conclusion: IF <i>some sort of interconnection</i> THEN <i>you could pull that out</i> p second conclusion: <i>some sort of interconnection</i> (form)		
Abductive (AB)	Modifying or introducing a new behaviour (mode of operation) for the concept	you could now open this up and now you've got like a double seat, double height, um, lounge seat. Or you pull the pin on this thing and you've got three seats.	[Max] Client Review – Lynn & Todd
	q a given function: to give different seating configurations [Darren] Client Review – Todd ----- $p \Rightarrow q$ first conclusion: IF <i>now open this up</i> THEN to give different seating configurations p second conclusion: <i>now open this up</i> q a given concept: <i>now open this up</i> $p \Rightarrow q$ first conclusion: IF <i>pull the pin on this thing</i> THEN <i>now open this up</i> p second conclusion: <i>pull the pin on this thing</i> (mode of operation)		
Abductive (AP)	Reframing the concept as a different kind of concept from	Or if that was open you could do like this. With different directions you could turn it into	[Max] Client Review – Todd

Reasoning Frame	Criterion	Example	Source
	what is actually proposed	a rocker, just kind of an idea there.	
	<p>q a given function: <i>to give different seating configurations</i> [Darren] Client Review – Todd</p> <p>-----</p> <p>$p \Rightarrow q$ first conclusion: IF <i>rocker</i> (concept) THEN <i>to give different seating configurations</i></p> <p>p second conclusion: <i>rocker</i></p> <p>q a given concept: <i>rocker</i></p> <p>-----</p> <p>$p \Rightarrow q$ first conclusion: IF <i>that was open</i> THEN <i>rocker</i></p> <p>p second conclusion: <i>that was open</i> (form)</p>		
Abductive (AU)	Framing alternative mode of user operation	... from this as well, kind of what you did with the third concept so now you can remove the cushion, flip it over, sit on the cushion	[Don] Client Review – Adam
	<p>q a given concept: versatile, functional piece</p> <p>-----</p> <p>$p \Rightarrow q$ first conclusion: IF <i>remove the cushion, flip it over, sit on the cushion</i> (mode of user operation) THEN versatile, functional piece</p> <p>p second conclusion: <i>remove the cushion, flip it over, sit on the cushion</i></p>		
Abductive (AC)	Framing alternative context of use	It's not gonna be something where you're gonna have you[r] tablet or laptop or anything. This is - to me, it's a brainstorming, it's informal meetings. There's probably a whiteboard.	[Gary] First Review – Todd
	<p>q a given concept: casual chair</p> <p>-----</p> <p>$p \Rightarrow q$ first conclusion: IF <i>it's a brainstorming, it's informal meetings</i> (alternative context of use) THEN casual chair</p> <p>p second conclusion: <i>it's a brainstorming, it's informal meetings</i></p>		

In this volume, Christensen and Ball (2014) coded instances of mental simulation when an initial representation is changed through a progression that finishes with a final, changed representation. Instances of mental simulation overlap with our codes for abductive reasoning that relate to Modifying or introducing a new form for the concept (AS) and Modifying or introducing a new behaviour (mode of operation) for the concept (AB). For example, Christensen and Ball provide an example of mental simulation in a section in the second undergraduate industrial design review in which the instructor Gary provides recommendations to Adam on ways to keep the chair stable on the floor while covering the underlying structure.

In this instance, Todd has previously introduced modular forms that could be transformed into a seating arrangement. The observed fact is the function, to connect the multiple modules chairs. Max introduces the solution principle of a removable a support (“you could pull that out”). He proposes a new type of “interconnection” as a form enabling the solution principle. Transforming this text into the notation for innovative abductive reasoning proposed by Roozenburg (1993) and then extended by Kroll and Koskela (2014), abduction proceeded in this example as follows:

q	given function = connect multiple chairs

$p \Rightarrow q$	first conclusion: IF <i>you could pull that out</i> THEN connect multiple chairs
p	second conclusion: <i>you could pull that out</i>
q	given: <i>you could pull that out</i>

$p \Rightarrow q$	first conclusion: IF <i>some sort of interconnection</i> THEN <i>you could pull that out</i>
p	second conclusion: <i>some sort of interconnection</i>

The hypotheses that Todd would then need to test include determining whether the solution principle of a ‘removable support’ is practical and whether the ‘interconnection’ is an appropriate form.

Figure 2 presents the tallies of the coding for the industrial design course transcripts analyzed. We do not show the tallies for the entrepreneurship course because only one presentation, the Tumbler Team, contained any instance of abductive reasoning. As expected, those presentations displayed instances of deductive reasoning about design quality only. To compare the frequency of occurrence of codes, the total count of codes per transcript are normalized to the total count of codes per code category. In counting the instances of evaluations of design quality, each distinct judgment of a concept’s attribute is counted. Where a person repeats an evaluation or states a similar evaluation toward the same attribute of the concept, the evaluation is counted only once. For example, in the Final Review for Adam, junior undergraduate student Adam appraises his seating concept as “comfortable” and the storage as “useful” and “nice”:

Adam: it was both comfortable [CA] it was useful, and it was also has a nice, ah, storing capability [CA].

The “useful” and “nice” attributes of the “storing capability” of the concept are counted once.

For the abductive inferences, each new hypothesis $p \Rightarrow q$ is counted as one instance of abductive reasoning. As shown in Table 2, there were instances in which the abductive inference was recursive. In such cases, each new hypothesis is counted as an instance of abductive reasoning.

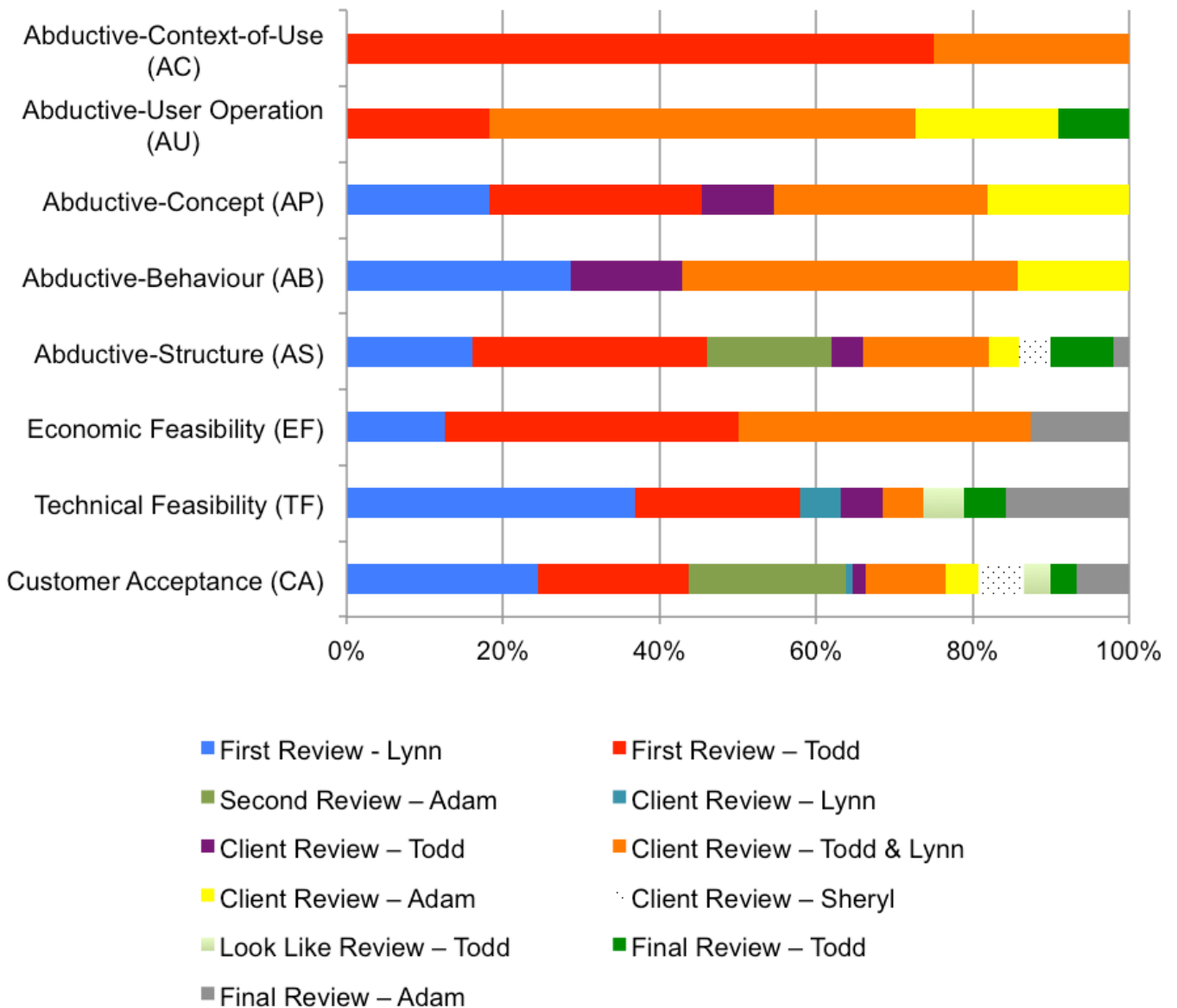


Figure 2. Descriptive results of the content coding

Several general trends are illustrated in Figure 2. First, propositions about Customer acceptance were reviewed in all of the sessions, but Economic feasibility was not regularly reviewed. While there were abductive inferences about structure (form) across most of the transcripts, there were comparatively fewer inferences about behaviour, that is, how the concepts would work. All transcripts except Sheryl's expressed abductive inferences about concept, suggesting that the design students and instructors explored alternative frames about 'seating' *per se*. Only Todd considered alternative contexts of use. In a frequency analysis of the codes, other trends are evident. Consistent with findings by Yilmaz and Daly (2014) in their analyses of design review conversations in a mechanical engineering design course and a dance course, the most frequent type of feedback is about the design (artifact) quality. Second, the number of deductive and

abductive inferences decreases over time. The most inferences occur during the first review meeting and during the client review, likely due to the purpose of the meeting – to discuss concepts and troubleshoot problems identified. The decrease over time suggests less exploration (abduction) and fewer judgments of tangible facts about the prototypes (deduction) probably because many of the problems (would) have already been ‘designed out’. This is consistent with our prior research showing that the narrative scope, that is, the breadth of frames, of design concepts tends to narrow over time (Song, Dong, & Agogino, 2003). During the coaching sessions themselves and the final review, there is a decreasing frequency of evaluations based upon the characteristics of the design concept and a decreasing frequency of abductive inferences. There is a much higher frequency of occurrence of abductive inferences proposing structural changes rather than mode of operation although there is a long sequence of discussion in the Client Review for Lynn and Todd, wherein the participants try to solve the problem of making the seating system reconfigurable.

While we were able to identify forms of reasoning that could lead up to a decision, explicit decisions were not evident in any of the transcripts analyzed. We could not conclude whether confirmation utterances such as ‘yeah’ or appraisals such as ‘I think the idea of this is kinda neat’ were actual decisions to proceed with a concept or whether in the latter case it is simply a judgment of the quality of an idea. Our coding takes the more conservative interpretation that they are either non-lexical conversational back channels or appraisals, e.g. of customer acceptance, respectively. In research by Ensici, Badke-Schaub, Bayazit, and Lauche (2013) on decisions taken by a design team tasked with designing a document organizer, the decisions were also implied rather than being explicit. In one excerpt quoted in their research, two participants reject an idea for a scanning functionality, with the researchers noting that the rejection as follows: “But it is not possible for us to solve this technology. It wouldn’t come to a conclusion.” The participants do not explicitly state, “We should not proceed with this alternative.” In our other research on design decision making in which the experimental design explicitly asked the participants to state their decisions, we were able to obtain more explicit statements of decisions such as, “It doesn’t seem like it’s technically feasible... I didn’t like the second project.” (Dong et al., Accepted 24 October 2014) and “I was leaning towards i5 [Intel microprocessor] as well.” (Dong, Sarkar, Yang, & Honda, 2013).

4.2. Purposes of Generative Sensing

In this section, we propose three functions of generative sensing. As these examples will demonstrate, the task of design evaluation was not strictly deductive, starting from given criteria to a conclusion. Rather, the evaluations can lead to new abductive hypotheses, and, when they do not, this lacuna may provide a tacit quality signal.

We identified several instances in the industrial design reviews of conversations starting from a deductive analysis, which led to a new abductive inference, which then set up a new cycle of design concept generation and evaluation, in other words, a pattern of generative sensing. In this pattern, a negative evaluation of a concept instigated an abductive inference to resolve the problem. Thus, the first function of generative sensing is to provide a solution (an inference to a causal explanation) to the negative evaluation of the design concept. This inference may then be

judged according to the existing criteria. In the Client Review for Todd, Darren judges Todd's concept of providing "plates" that move so as to create flexibility in seating configuration:

Todd: Yeah, it's intriguingly with these three sections you'd be able to get completely different seating and have a little bit of out [CA]. I think the challenge is how do you connect them all. [TF]

Rather than simply leaving this as a problem for Todd to solve, Max proposes a structural modification:

*Max: So what you have here it shows them sagged but **if there was some sort of interconnection [AS] where you could actually pull that out and turn it into chair [AB] or-***

Max's inference of the new form ("interconnection") then leads to a potential new concept as a "rocker", which Todd appraises as "could be cool".

In Todd's Final Review, Devon, a client and industrial designer, offers a critique (judgment) in the form of an inference about the material choices:

*Devon: Safe to say that the entire object being upholstered then? Have you thought about **guess what I am doing may be use different colors right now? So maybe the colors are different materials possibly [AS] so upper is maybe softer the others are a little more rigid [AS]?***

Todd then responds with a potential change to the material choices, which would affect his concept's mode of operation. He also evaluates the proposed modification.

*Todd: Yeah, actually, **the bottom, ah, the base could be like a heavier material [AS]. That way it's even more stable [TF], and the top could be like a lighter material [AS]. And, ah, the different sections allow for, ah, different color study, such as like mon-, monochromatic [unintelligible] or it could be like any other kind of study.***

As stated previously, only the Tumbler Team's presentation and question and answer session displayed any example of abductive reasoning. While the questioning by the expert panel to the Tumbler Team tends toward confirmatory or explanatory questioning, such as technical feasibility or the method to obtain financial projections, we identified three instances of generative sensing. All were based upon instances of AP (Reframing the product as a different kind of product from what is actually proposed). In response to a question by Nicole, a professor and the entrepreneurship program director on the expert panel, whether the team had considered their trashcan as a giveaway (known fact is the value or function "to promote"), itself an alternative framing of the product, Sabrina, who has the role of communication in the team, responds with the following:

Sabrina: We also envision we one day having this be like something – like envision

The clients' review of Todd's concept, though, contains ample evidence of generative sensing following their evaluations. The clients have taken as a fact that Todd aims to make a reconfigurable seating system. Don proposes a "perch" as an alternative concept and an alternative context of use such as "brainstorming, and other things. So they don't want to take the time to physically sit in a chair." This then spurs a series of other inferences such as Max's comment of it "being made in three different, three different kinds of technology [AS]" with a base "that would be substantially weighted - so this thing won't slide around or whatever [AB]" and a "house" for "whatever the pivot point is [AS]". The section of dialog between 02:18 and 06:46 is the most productive in terms of occurrence of abductive reasoning. We note also, as shown in Figure 2, that the coding of 'Client Review – Lynn' identified no instances of abductive reasoning. We conjecture, therefore, that this absence is a tacit signal on the quality of the design concept. By not being able to "figure out" or "explain away" some of the issues identified in the evaluation of the concept, the absence of generative sensing may provide an indication of the poor quality of the concept. Thus, the second function of generative sensing may be to provide a quality indication without explicitly judging the concept.

McDonnell (2014) and Adams, Forin, Chua, and Radcliffe (2014) present an alternative interpretation for the purpose of generative sensing. In McDonnell's analysis of the design reviews, she points to portions of the review conversations in which the critical feedback from the clients and design instructors serve as scaffolding or resources for the students to justify their preferred design options. In other words, the instructor or client's critiques which we would have coded as inferences to changed forms or changed behaviours are not necessarily intended to be acted upon. Rather, the critiques operate as rhetorical instruments. The concepts (artifacts) are themselves rhetorical devices to convey justifications for the student's approach to the design problem. The inferences (suggested changes) may serve as a means to invite the student to identify the essential elements of the design options, which would irrevocably compromise the design if modified as suggested by the instructor or client. Similarly, Adams et al. describe these inferences as a "suggest don't tell" approach to design teaching; when design coaches make suggestions (inferences), they are intended to encourage students to make their own decision rather than to prescribe a course of action. Thus, the third function of generative sensing may be to test the student's commitment to the present design concept. The inferences provide a starting point for deliberations on the fit for purpose of the design concept, which may lead to a change in the concept if the student is in agreement. Alternatively, the inferences provide an opportunity for the student to defend the concept, to rebut proposed changes that would alter the intended properties of the design concept. McDonnell argues that inviting students to engage in this type of conversation develops the student's professional competency to take a position and justify it. A quote identified by Lande and Oplinger (2014) of Gary responding to a student helping Todd to resolve a problem during his look-like review summarizes this point: "He's gotta discover that".

The likelihood with which the student would perceive the inference as a suggestion may depend upon the studio's norms of pedagogic practice. Wolmarans (2014) analyzed the structure of the mechanical engineering design course according to Basil Bernstein's concept of framing (2000), the extent to which an instructor retains apparent control over the selection, sequencing and pacing of what knowledge matters. When the instructor controls the criteria for these, the framing is considered strong; where the student controls them, the framing is considered weak.

Wolmarans concluded based upon an analysis of the syllabus that the framing of the mechanical engineering design course is weak because the selection of theoretical knowledge and the sequence of its application are left to the students. In the industrial design course, neither the syllabus nor the design brief contained any explicit expectation that design knowledge should come from a particular school or discipline or way of designing; hence, it is possible to conclude that the framing is also weak. Given the apparent expectation that the students in the industrial design course should be responsible for selecting the knowledge needed to solve their self-constructed design response to the brief and the sequence in which to approach the design brief, in the context of these design review conversations, it is very plausible that generative sensing is a mechanism to test the student's approach and commitment to the design concept.

5. Implications for Design Thinking

The concept of design evaluation has at least two possible meanings in design practice. Broadly construed, design evaluation entails the critique and assessment of not-yet-fully elaborated concepts in relation to their suitability to the brief, but with a view to their further elaboration and augmentation. This type of evaluation takes place throughout the design process, and is the type of design evaluation evidenced in the DTRS10 transcripts. In the strict sense of design evaluation, evaluation means the determination of the quality (value or worth) of a design concept against established objectives as a function of one or more its attributes (Thurston, 1991). The development of explicit design evaluation procedures and metrics has been recognized as a crucial part of this task, procedures and metrics that require deductive reasoning from established rules.

The question raised in this research is whether it is appropriate that design evaluation, even in its strict sense, should not include any other form of reasoning than deductive logic. Stated in another way, do abductive reasoning and generative sensing have any role to play when determining the value of a concept? We believe it does. Individuals and organizations tend to choose activities that lie in the vicinity of current activities rather than more distant ones (Levinthal, 1997; March, 1991). Evaluation procedures and metrics that call for mental processes suited to deductive reasoning may thus have the downside of limiting “mental processes that underlie the identification of cognitively distant strategies or positions, especially the choice or formation of appropriate representational structures to ‘look into the distant’” (Gavetti, 2012, p. 273). In other words, if we only look at what we've got, we may not see what we could have. We therefore call for a balance of deductive and abductive reasoning in design evaluation. Although design evaluation in its strictest sense will only entail deductive logic ($p \Rightarrow q$ Something with quality should be selected; p This concept has quality; q This concept should be selected.), we suggest an additional generative sensing loop in which new propositions are invented as a means to explain the decision.

q	given: <i>concept is selected</i>

$p \Rightarrow q$	first conclusion: IF <i>new inference</i> THEN <i>concept is selected</i>
p	second conclusion: <i>new inference</i>

In the data analyzed, new inferences included alternative structural forms, other modes of use, new users, and new contexts of uses. Our list shown in Table 2 should be seen as provisional and specific to this design context; we expect that the list would be expanded as we uncover other ways in which individuals produce abductions in design.

As our results show, design review conversations have elements of deductive and abductive reasoning. Patterns were exhibited in which abductive inferences followed negative evaluations of a design concept. The innovative abduction subsequent to the design evaluation is likely to be a crucial source of superior design performance stemming from the students' or coaches' mental ability to overcome the bounded rationality of the information (evidence) available at hand.

In our analysis, we have followed current theorization about innovative abduction in design as progressing from function, or value, to form. The results illustrate that innovative abduction does not necessarily start or end with these two end-points. The situation may be that the direction of the innovative abduction is more related to divergent or convergent thinking. In divergent thinking, function follows form: it flows outward, generating possibilities that one might not ordinarily consider (Finke, 1995, 1996). In convergent thinking, by contrast, form follows function: we make sense of apparently disconnected facts that we apply to a particular situation. Research in entrepreneurial opportunity recognition by undergraduate and MBA students matched the type of insights required for opportunity recognition with students' learning style. Dimov (2007) found that evaluating outside-the-box insights requires a divergent, multiple-perspective learning approach, whereas evaluating logic-driven insights requires a convergent, disciplined learning approach. In a recent contribution, Gielnik, Krämer, Kappel, and Frese (2014) investigated the role of divergent thinking in people's general ability to identify multiple and original ideas in opportunity recognition. In their treatment, divergent thinking was considered the end product of more specific cognitive processes, such as conceptual combination, analogical reasoning, and abstraction (Mumford, 2003; Ward, 2007; Welling, 2007). More specifically, they established that active information search enhances the positive effects of divergent thinking on business opportunity identification. Business opportunity identification transmitted an indirect effect of divergent thinking on innovativeness of product/service innovations, which was contingent on active information search. By contrast, deductive reasoning and convergent thinking led to a single conventional answer rather than a range of creative, unconventional means-ends relations. While our analysis did not determine whether the abduction were divergent or convergent, the results suggest that the direction of abduction is not likely to be simply one or direction or the other as currently theorized (Dorst, 2011; Kroll & Koskela, 2014; Roozenburg, 1993; Zeng & Cheng, 1991). Rather, abductive reasoning can be directed toward both divergent and convergent thinking. In the former, it creates inferences about new possible use contexts, for example, that could be explored. For the latter, it infers new forms that resolve identified problems to reach a solution. The logic of abduction is a productive cognitive strategy during design evaluation in both its strict and broad sense because abduction creates verifiable hypotheses to expand the space of possibilities or to create a pathway to a workable solution. Robust design conversations need both deductive logic and generative sensing supported by abductive reasoning.

6. Implications for Teaching and Design Evaluations

Schön (1987) provides the classic description of the interaction between Quist, the master design tutor, and the student, Petra. In it, Schön portrays Quist modeling reflection for Petra. In these interactions between the design coaches, clients, and design students, we see evidence of a different type of interaction: a design evaluation that contains generative sensing. The generative sensing turns what are design evaluations into *ipso facto* designing during design evaluation. The following excerpt of the response by Adam to the comments by the clients demonstrates this occurrence:

Adam: Um, I personally, ah, in my heart of hearts, I, I just love the, ah, I just love the uniformity of, ah, just all one piece [CA]. But if you were worried about durability [TF], I suppose you could put a rim on the bottom [AS]. Ah, and that wad, ah, solve some durability –

Rather than disagreeing with the clients' comments, Adam proposes a structural change through a new form, the 'rim'.

To this, Max responds:

Max: I, I liked this one from the start [CA]. And, again, I mean, I – you know with that self-skinning, one person sits down with a pencil in their pocket and there could be some issues [TF]. But if we can work through those issues, I really like it.

Max hints at solutions to the problem of people scratching the surface with pencils, and suggests that they “can work through those issues”. Thus, a critical point of departure in productive design evaluations is that the design evaluations are not used simply to accept or reject a design concept; rather, they are opportunities for abductive inferences to propose new forms, mode of operation, mode of user operation, or context of use.

In the data set, we identified instances of generative sensing that explain away a problem, that is, generative sensing that explains anomalous evidence. It is altogether possible, though, that for a highly productive design concept, a positive evaluation could also elicit generative sensing to hypothesize new opportunities. When instructors explain away a problem, that is infer a solution, Tolbert and Daly (2013) noted that to the students this constitutes advice, which the students tend to follow. As such, instructors should be careful not to signal inadvertently to the student that their explanation is a best solution because this could dissuade students from engaging in additional exploration (Tolbert & Daly, 2013). Further, Tolbert and Daly (2013) suggest that positive criticism can also have the unintended consequence of leading students to believe that they have already identified the best solution, which also dissuades them from additional exploration. Thus, instructors should consider whether the generative sensing is intended to encourage explorative thinking or whether, given the design stage, it is intended to encourage the student to focus and converge. Given that design students struggle to synthesize or reconcile conflicting evidence (Mohedas, Daly, & Sienko, 2014), instructors should clarify that they are making an inference whilst making explicit the intended purpose of the inference.

Greater emphasis on the role of generative sensing is likely to have a substantial impact on the teaching of entrepreneurship to aspiring entrepreneurs and managers alike. On one hand, individuals tend to enjoy and defend the conformity provided by the familiar rather than the novel (Berns, 2008), maintaining the status quo despite its inferiority with respect to “what it might be”. Business people also display the ‘single-answer problem’ syndrome. When people are solving strategic problems, no matter the difficulty of the problem, the overwhelming bias is to treat them as a closed-form solution, where a unique, reliable and repeatable outcome is sought (Austen, 2012). Knowing that we have the answer and that it might be the right answer makes us comfortable. On the other hand, innovators have a natural tendency against the status quo and they take advantage of any occasion to question it and generate opportunities on how to improve it (Dyer, Gregersen, & Christensen, 2008). Helping students to develop skills in generative sensing is likely to encourage them to see beyond the familiar, avoiding committing their search prematurely towards *the* single answer and instead explore multiple interpretations of problems and solutions alike.

7. Conclusions

In this study, we have proposed that design evaluations consist of two mechanisms of reasoning: deductive analysis of existing data (the design concept as presented) and abductive reasoning explaining issues raised by the deductive analysis, which we term generative sensing. Based on the analysis of the DTRS10 data, we identified three potential functions of generative sensing. The first is to produce new hypotheses that explain or resolve issues identified by the deductive analysis. Thus, for example, rather than concluding an evaluation with a negative evaluation, the participant introduces an abductive inference to propose a resolution. These resolutions include proposed structural changes, behavioral (mode of operation) modifications, product framing, modes of user operation, or contexts of use. This is not an exhaustive list of abductive inferences. The second function is to provide a tacit judgment on the quality of the design concept. In the data analyzed, there were particular instances of deductive evaluation followed by abductive inferences and others with a marked absence of abduction. This inability to resolve issues, which basically means to reframe the design concept (Dorst, 2011) in some way so as to resolve the problems, is likely to indicate that the concept is unworkable. Finally, generative sensing may be a rhetorical device to open up dialog about the present design concept. The abductive inferences create opportunities for students to defend their design choices, and in so doing, professionalize them into the practice of design.

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