Generative sensing in design evaluation

Andy Dong, Faculty of Engineering and Information Technologies, University of Sydney, Sydney, NSW 2006, Australia
Massimo Garbuio and Dan Lovallo, The University of Sydney Business School, University of Sydney, Sydney, NSW 2006, Australia

The analysis of design review conversations from a junior-level undergraduate industrial design course and an entrepreneurship course uncovered a new pattern of design thinking. Design thinking during concept evaluation contains a recursive hypothesis-driven pattern that we name generative sensing. Generative sensing commences with deductive reasoning from established rules to a definitive conclusion in favour of or against a concept. These conclusions become the basis for new hypotheses that suggest actions to address problems or invite rebuttals to defend the original logic of the concept. Generative sensing is a pattern of design thinking that creates ways through the design problem by testing propositions in a recursive manner.

Keywords: decision making, design thinking, abduction

A normative model of the design process describes it as proceeding from concept generation to concept evaluation to concept selection (Nikander, Liikkanen, & Laakso, 2014). Design thinking alternates between divergent thinking during concept generation and convergent thinking during concept evaluation and selection (Leonard & Sensiper, 1998). Although scholars acknowledge iterative loops between these stages, the accepted practice is that concept evaluation should only examine the merits of a concept, determining the quality (value or worth) of a concept against established objectives as a function of one or more of its attributes (Thurston, 1991). To assist designers in this evaluation, researchers have proposed a number of metrics to prove or disprove the merits of a concept, such as its creativity (Nelson, Wilson, Rosen, & Yen, 2009; Oman, Tumer, Wood, & Seepersad, 2013; Shah, Smith, & Vargas-Hernandez, 2003; Verhaegen, Vandevenne, Peeters, & Duflou, 2013).

Concept selection follows concept evaluation, leading to the selection or consolidation of one or more concepts for further development. Here, too, 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). The preponderance of quantitative models for concept evaluation and selection, as compared to concept generation, suggest that they are two design stages most amenable to analytical thought.

Lost in the substantial body of scholarship on concept evaluation and concept selection, though, is the quality of the decision making process itself. Borrowing from the scholarship in strategic decision making (e.g., taking a decision to expand the scope of a company through a new product or service), a broad body of 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 (Fredrickson & Mitchell, 1984; Papadakis & Barwise, 2002). 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, & Sibony, 2015).Inthisstudy,itwas'how'theexecutivestalkedaboutthedecisionandits underlying assumptions that affected whether expectations (in terms of market share or profitability) were met, not 'what' financial analysis was performed.

Given prior scholarship, this research began with the intention of testing and questioning the normative assertion that concept evaluation entails analytical, convergent thinking. A high-quality design review conversation should exhibit a rigorous discussion of the merit of the presented concepts. We believe a highquality design review conversation should also hypothesise future possibilities. Laboratory studies of design concept evaluation and selection already show that the decisions do not consist exclusively of convergent, analytical thinking, and further that the form of logical reasoning influences the direction of the selection decision (Dong, Lovallo, & Mounarath, 2015). The empirical results of this study will point to a more substantial finding, a new pattern of design thinking. The research context consists 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 concern the evaluation of 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 about how much to fund, if at all, the proposed project (Bardolet, Fox, & Lovallo, 2011). The article describes the method of analysis and the recursive, hypothesis-driven pattern of the design thinking uncovered.

Theoretical frameworks

Concept evaluation is grounded in theories about normative decision-making methods. A rather substantial body of literature largely reaches the conclusion that whereas concept generation should entail divergent thinking processes, concept evaluation and concept selection should entail convergent thinking (Liu, Chakrabarti, & Bligh, 2003). Convergent thinking necessarily entails deductive reasoning to lead to definitive conclusions (Cropley, 2006). This advice is useful as far as it goes but is limited, as evidence is an insufficient basis for a strategic decision, and convergent thinking during concept evaluation may proscribe 'forward looking' for 'what might be'.

During merit-based concept evaluation, decision makers use evidence to evaluate design quality based upon existing rules and criteria such as the requirements or objectives. When we refer to evidence, we mean propositions that justify a belief; propositions may include inter alia:

observable properties of the concept, such as physical characteristics

arguments based upon belief or experience, such as professional standards

secondary data, such as consumer preference data

claims, such as conclusions drawn from prior evaluations of the design concept

However, relying on evidence alone to argue the merits of a concept is not likely to lead to a robust decision. Companies that are successful at innovation know the importance of discussing the assumptions behind evidence rather than simply taking 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 modelling' 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 result from improving conversations than from analysis. Even the tools used to support the conversation mattered. For example, in the researchers' words, 'the spreadsheet is an exceptionally poor tool for documenting and sharing the hypothesis of record. [.] The thinking underlying the calculations is what matters 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 a conversation is only about the results of the data, decision makers 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).

Second, to deliberate about what lies ahead 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.

Abductive reasoning is a form of logical reasoning that introduces new hypotheses to explain given observations. The concept of abduction in design is philosophically very powerful as it introduces a mechanism of discovery through a form of logical reasoning. In concept evaluation, abduction may introduce hypotheses to explain the evidence. Further, it may introduce hypotheses which if true would render the evidence irrelevant because the truth conditions can be changed by redesigning the concept. 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 value, the function, and an explanation (the form) for the design concept (Kroll & Koskela, 2014; Roozenburg, 1993). Innovative abduction is 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, to 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 about the form of the proposed product and its mode of operation which, if true, explain the 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
q	The conclusion:	p

Kroll and Koskela (2014, p. 372) extend the model of innovative abduction proposed by Roozenburg (1993) and Dorst (2011) into a two-step recursive inference. The first step involves the abduction of a concept given a function and the second involves the abduction of a form given the concept inferred from the previous step, as shown below:

q	a given fact:	*function*
$p \Rightarrow q$	first conclusion:	IF *concept* THEN *function*
p	second conclusion:	*concept*
q	a given fact:	*concept*
$p \Rightarrow q$	first conclusion:	IF *form* THEN *concept*
p	second conclusion:	*form*

Each abduction may only be a partial resolution of the design 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.

In sum, while it has been claimed that concept evaluation and selection should only entail convergent thinking, at issue is whether the forms of logical reasoning present in naturally occurring design concept evaluations support this normative model. In particular, if concept evaluation were strictly convergent, then it should be characterised predominantly by deductive reasoning without any abduction, as found in priorresearch (Galle, 1996). We have presentedsome arguments to suggest that innovative abduction may occur even during concept evaluation, as the evidence can be ambiguous, conflicting, or inconclusive.

This study investigates the forms of logical reasoning naturally occurring in design concept evaluations. We have previously studied the effect of forms of logical reasoning at the point of selecting one or more options from a discrete set of non-modifiable options by a committee not involved in the generation of those options (Dong et al., 2015). That study showed that a deductive reasoning frame by decision-makers can suppress the likelihood of accepting novel concepts. This study goes further by investigating the effect of forms of logical reasoning present during the evaluation of concepts developed by the designer throughout a complete design process(i.e.,from initial concept through to final prototype).The interrogation of forms of logical reasoning over a longer period of time may permit a pattern of design thinking to be uncovered.

Methodology

Design concept review conversations were obtained from a database recorded for the Design Thinking Research Symposium (DTRS) 10 (Adams, 2015). Two polar types of design review conversations were selected for this study. The first set of conversations came from a junior (third-year) industrial design course. In this course, students were asked to design a new seating concept. The project brief offered scope for the students to explore possibilities for a seating concept rather than to solve a defined problem. The second set of conversations came from the final presentations in an entrepreneurship course. Student teams presented their final concepts to potential investors. The selection of these two types of polar types of conversations was intended to make deductive and abductive reasoning more observable (Eisenhardt, 1989). Given the scope and duration of the industrial design course, the industrial design context is more likely to contain elements of 'design thinking', a core element of which is abductive reasoning (Dorst, 2011). In contrast, the entrepreneurship course project presentations were comparatively shorter. The presentations should emphasize 'hard' evidence conducive to managerial decisionmaking. The students' presentation should present definitive conclusions deduced from established premises and the evidence at hand because the committee would make funding decisions regarding the teams' concepts. Pitches to investors for an entrepreneurial business opportunity emphasise verifiable evidence, such as marketplace acceptance and the size and accessibility of the market, because an appraisal of this evidence determines the investment decision (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. As well, there is limited opportunity for the students to redesign their concept in light of the committee's evaluations. Patterns of occurrence of abductive reasoning in the industrial design review conversations could therefore be considered relevant to contexts involving design thinking but not necessarily to other contexts.

For the industrial design course, transcripts from the initial design review to the client review and the final review were analysed. Transcripts were chosen on the basis of continuity of the dataset across all the review sessions for the same industrial design student. Eleven transcripts containing about 2 h of dialogue from the junior industrial design course and all six presentations from the entrepreneurship course, each lasting 10e15 min, were analysed.

To code the extent to which decision makers applied deductive reasoning to evaluate the merit of options, instances of appraisals of a concept were identified (Dong, Kleinsmann, & Valkenburg, 2009). Merit-based evaluation necessarily entails deductive reasoning when the conclusion logically follows from established criteria. Taking the Customer acceptance excerpt from Table 1, deductive reasoning would be described in logical notation as:

$p \Rightarrow q$	a given rule:	IF *a concept has functional utility* THEN *a concept is useful*
q	a given fact:	*that's a great utility*
q	the conclusion:	*a concept is useful*

Yilmaz and Daly (2015) coded these types of evaluations as feedback on artifact quality using similar criteria. Merit-based evaluation of design concept quality were grouped according to the categories shown in Table 1 (Kelley

Table 1 Criteria for coding discussions of design quality - merit-based evaluation

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 this is a great idea 'cause that's a great utility, 'cause this is a real negative wasted amount of space. I think that's a good idea.	[Gary] 1-ID-jr-First Review-Lynn
Technical factors (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 this is very difficult to do in foam, it's very almost impossible so that's something like the chair like form you can bring that in and fit it to these dimensions. It's very difficult to fit in foam this first one.	[Gary] 3-ID-jr-Client Review Adrianna

Economic factors (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 just don't know how we would make it, make it - affordable and it's uh.	[Darren] 3-ID-jr-Client Review-LynneTodd

& Littman, 2001). The frequency of merit-based evaluations will be used to determine the degree of deductive reasoning. It is important to note that we coded instances of logical reasoning, and not simply evaluative comments about a design concept or project without exhibiting any evidence of reasoning. For example, in the first design review with her coach, Lynn presents a number of concepts but is unsure how to progress the concepts. After describing her concepts, her responses to Gary's comments are generally limited to 'Mm-hmm' or 'Okay'. Probably sensing that Lynn may lack motivation or confidence in her concepts, Gary concludes by saying, 'Cause you got some really great ideas. It'd be a shame if they didn't get developed, developed -'. His statement would not be coded as a merit-based evaluation exhibiting deductive reasoning as there is no criteria (rule) from which the evaluation of 'great' logically follows. Evaluations of the student, presentations, or the design process were not considered.

To analyse for abductive reasoning, a coding scheme grounded in the theories of abductive logic in design was developed. Two important extensions were made to these theories. 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 the 'interaction design', a non-trivial inference especially since innovative designs tend to improve upon user interaction (Saunders, Seepersad, & Holtta-Otto, 2011). The mode of user operation is contingent both upon the mode of operation and on the form. For example, the touch screen interface on a cell phone depends upon capacitive sensing (mode of operation) and the flat form of the phone. Thus, the mode of user operation should be explicitly included as a sub-problem to be resolved through abduction. The mode of user operation can be described in abductive logic notation as shown in Table 2:

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

Previously, models of abductive inference in design linked reasoning from function to form without consideration that it is possible to situate the concept in a different context. Situating the concept changes the interpretation of its function, what Gero and Kannengiesser (2004) describe as type-3 reformulation in their 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. 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 the context of use of the adhesive to the office, a new function for the adhesive could be inferred: temporary notes. Abduction to a new function can be described in logical notation as shown in Table 3:

Table 4 describes the criteria to code for abductive reasoning and example excerpts including the abductive reasoning in the logic notation described by Kroll and Koskela (2014). The first two codes, AS and AB, relate to the inference of a form and mode of operation as previously canvassed by Roozenburg

Table 2 Inference to mode of user operation

q	a given fact:	*function* – *e.g., data input*
$p \Rightarrow q$	first conclusion:	IF *mode of operation* – *e.g., capacitive sensing* THEN *function*
p	second conclusion:	*mode of operation*
q	a given fact:	*mode of operation* – *e.g., capacitive sensing*
$p \Rightarrow q$	first conclusion:	IF *mode of user operation* – *e.g., touch screen* THEN *mode of operation*
p	second conclusion:	*mode of user operation*

Table 3 Inference to function

q	a given fact:	*concept* – *e.g., microsphere adhesive*
$p \Rightarrow q$	first conclusion:	IF *context of use* – *e.g., professional office* THEN *concept*
p	second conclusion:	*context of use*
q	a given fact:	*context of use* – *professional office*
$p \Rightarrow q$	first conclusion:	IF *function* – *e.g., create temporary notes* THEN *context of use*
p	second conclusion:	*function*

Table 4 Criteria for coding discussions for abduction – opportunity-based evaluation

Code	*Criteria*	*Example*	*Source*
Abductive – Structure (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 -connect multiple modules	[Max] Client Review – Todd
	q	a given function:	
	$p \Rightarrow q$	first conclusion:	IF *you could actually pull that out* THEN *connect multiple chairs*
	p	second conclusion:	*you could actually pull that out*
	q	a given concept:	*you could actually pull that out*
	$p \Rightarrow q$	first conclusion:	IF *some sort of interconnection* THEN *you could actually pull that out*
	p	second conclusion:	*some sort of interconnection* (form)
Abductive – Behaviour (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 *now open this up* THEN *to give different seating configurations*
	p	second conclusion:	*now open this up*
	q	a given concept:	*now open this up*
	$p \Rightarrow q$	first conclusion:	IF *pull the pin on this thing* THEN *now open this up*
	p	second conclusion:	*pull the pin on this thing* (mode of operation)

Table 4 (*continued*)

Code	*Criteria*	*Example*	*Source*
Abductive – Product (AP)	Framing the concept as a different kind of concept from what is actually proposed	Or if that was open you could do like this. With different directions you could turn it into a rocker, just kind of an idea there.	[Max] Client Review – Todd
	q	a given concept:	to give different seating configurations [Darren] Client Review – Todd
	$p \Rightarrow q$	first conclusion:	IF *rocker* (concept) THEN *to give different seating configurations*
	p	second conclusion:	*rocker*
	q	a given concept:	*rocker*
	$p \Rightarrow q$	first conclusion:	IF *that was open* THEN *rocker*
	p	Second conclusion:	*that was open* (form)
Abductive – User (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
	q	a given concept:	versatile, functional piece
	$p \Rightarrow q$	first conclusion:	IF *remove the cushion, flip it over, sit on the cushion* (mode of user operation) THEN versatile, functional piece
	p	second conclusion:	*remove the cushion, flip it over, sit on the cushion*
Abductive – Context (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
	q	a given concept:	casual chair
	$p \Rightarrow q$	first conclusion:	IF *it's a brainstorming, it's informal meetings* (context of use) THEN casual chair
	p	second conclusion:	*it's a brainstorming, it's informal meetings*

(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. Where more than one abductive inference is shown, 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. 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 innovative abduction, 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.

The transcript was coded according to utterances, a segmentation of the dialogue according to turn-taking. Each utterance can be assigned one or more codes depending upon the number of instances of deduction or abduction present in the utterance. One author coded all of the transcripts over multiple passes until the codes no longer changed between intervals, which last at least one week. To verify the reliability of the coding, another author was trained on the coding scheme using one training transcript from the junior industrial design course containing approximately 20 min of dialogue. Discrepancies were discussed to reconcile the coders' disagreements on the application of the codes, and adjustments were made to the coding when the disagreements were resolved. Intercoder reliability was calculated by using another transcript containing approximately 06:46 min of dialogue (approximately 5% of the total duration). The same two authors independently coded this reliability transcript with no consultation. The intercoder reliability (Krippendorf's alpha calculated using SPSS (Hayes & Krippendorff, 2007)) on this transcript is 0.95, which is considered acceptable for qualitative research (Lombard, Snyder-Duch, & Bracken, 2002).

Once instances of forms of logical reasoning were identified, one coder identified episodes of evaluation. An episode of evaluation is a contiguous block of utterances that contain deduction or abduction and refer to the same aspect of the present concept. An episode can be a single utterance. The occurrence of deduction and abduction within an episode will be used to identify patterns of logical reasoning.

Results

As these examples will demonstrate, the task of design evaluation included all forms of logical reasoning. Table 5 reports on the frequency of occurrence of the forms of logical reasoning within an utterance by an individual for all of

Table 5 Contingency table showing frequency of forms of logical reasoning across industrial design review conversations

	Abduction Present	Abduction Absent	Total
Deduction present	14	87	101
Deduction absent	52	809	861
Total	66	896	962

the design review conversations in the undergraduate industrial design course. Logical reasoning was identified in approximately 20% of the utterances. Counting the frequency of forms of logical reasoning by utterance is more conservative than counting by episode of evaluation. Using a more encompassing definition of design evaluations, Christensen and Ball (2015) found that the industrial design transcripts consisted of approximately 36% evaluations. Had we applied their definition of evaluations, the frequency of occurrences of Deduction Present - Abduction Absent would have increased and Deduction Absent - Abduction Absent would have increased in the same proportions. If a significant difference is found in this method of counting, then the significance will be even higher if a proportion of the frequency of occurrences of Deduction Present - Abduction Absent and Abduction Present - Deduction Absent were included in the frequency of occurrences of Deduction Present and Abduction Present.

The forms of logical reasoning differed significantly in terms of their frequency of co-occurrence ($c^2(1) = 8.66$, $p = .0033$). Notably, the frequency of occurrence of deduction and abduction within a single utterance is non-zero and significantly differs from the other patterns. This result confirms that deduction and abduction do not occur together by chance. Therefore, the finding of the number of Deduction Present - Abduction Present is significant and suggests an important pattern of logical reasoning in design evaluation.

The transcripts were further analysed for the co-occurrence of deduction and abduction within a single utterance (14 occurrences) or within an episode of evaluation (13 occurrences). Two situations in which deduction and abduction co-occurred in the same utterance or episode were identified: abductive hypotheses that resolve problems by proposing a solution that may then be assessed through further actions; or, abductive hypotheses that propose conditions that undermine the present concept.

As an exemplar of abductive hypotheses that resolve problems, during the client review, junior undergraduate student Todd introduced three seating concepts. In two of the concepts, Todd wanted the seat to transform into different seat types. To achieve this behaviour, one of the concepts contained multiple pieces of foam, each constituting a module that should be connected but transformable. However, he struggled to identify a means to connect the modules and deduces that his 'permanent fixture of this being able to rotate' would make the cushions sag. Rather than ending the conversation on this evaluation, Max, the client and an engineer, reaffirms the desired value (function): to connect the multiple modules. Max assists Todd by inferring a structural modification based upon Todd's conclusion:

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* [AB] and *turn it into chair* [AP] or –

Max introduces the solution principle as a mode of operation ('you could actually pull that out'). He proposes a new type of 'interconnection' as a form enabling the solution principle, leading to a revised product frame, a 'chair'. Transforming this text into the logical notation, innovative abduction proceeded in this example as follows:

q	a given function:	connect multiple modules
$p \Rightarrow q$	first conclusion:	IF *you could actually pull that out* [AB] THEN connect multiple modules
p	second conclusion:	*you could actually pull that out*
q	a given mode of operation:	*you could actually pull that out*
$p \Rightarrow q$	first conclusion:	IF *some sort of interconnection* [AS] THEN *you could actually pull that out*
p	second conclusion:	*some sort of interconnection*

Notably, neither hypothesis is true nor false; instead, each hypothesis is performative as each suggests that actions could occur to test it. The hypotheses that Todd would need to test include determining whether the solution principle of a 'removable support' is desirable and whether the 'interconnection' is an appropriate form. In the Looks Like review, Todd explains that the hypothesis that there is a removable interconnection turns out to be false because the clients preferred a chair that could rotate, thus eliminating the desirability of a removable interconnection. Instead, the clients preferred the modules to rotate (desired function). Todd hypotheses a vertical pole (Abduction - Structure) through the modules, but his instructor, Gary, believes it will not work and suggests some experiments to verify Todd's hypothesis. During the final review, Todd demonstrates a prototype using a 'lazy Susan' as the mechanism to rotate the top module, indicating that Todd's vertical pole hypothesis was also false. An abductive hypothesis may also infer a set of conditions that may undermine the present design concept. During a review between clients Darren and Jason and design student Adam, Adam presents a stool concept that has a pull-out shelf. Rather than referring to this concept, Darren picks up Adam's bench-like concept and proclaims that Adam's bench concept is 'kinda neat', a positive judgement of his concept. Darren further remarks though that if Adam were to assemble the benches together in a particular organisation (mode of operation) or up against the wall (context of use), then it may undermine his bench concept. Darren asks Adam to 'take that into consideration'. In this situation, the inferences do not resolve a problem. Instead, they infer conditions that would undermine the concept and thus challenge the current design concept. In the final review, Adam shows a seat that is a set of perches. The solution borrows from the benches concept the characteristic of being placed adjacent to each other, but without the depth problem that undermined the bench concept.

In the entrepreneurship presentations, only the Tumbler Team's presentation and question-and-answer session exhibited any instances of abduction. This finding is not surprising since the intent of the presentations is to show a complete design concept with limited, if any, opportunity for modification. The teams needed to present definitive conclusions on the merits of their designs, as the committee would based their decisions upon the veracity of the teams' claims. During the Tumbler Team's presentation, Nicole, a professor and the entrepreneurship program director on the expert panel, asked whether the team had considered their trashcan as 'a promotional item' (known fact is the value or function 'to promote').

While it is unclear whether the comment is intended to question the plausibility of selling the trashcan to individual consumers or is itself an innovative abduction that is reframing the product, Sabrina, who has the role of communication in the team, responds with the following statement:

Sabrina	We also envision we one day having this be like something – like envision that *the trashcan is green, and it's a promotional thing for a waste management* [AP]. So *half of our proceeds would go to a cause* [AB] so that way everyone loves to give back [unintelligible] so that's something that could also happen with our product.

q	a given function:	to promote
$p \Rightarrow q$	first conclusion:	IF *a promotional thing for a waste management* [AP] THEN to promote
p	second conclusion:	*a promotional thing for a waste management*
q	a given concept	*a promotional thing for a waste management*
$p \Rightarrow q$	first conclusion:	IF *half of our proceeds would go to a cause* [AB] THEN *a promotional thing for a waste management*
p	second conclusion:	*half of our proceeds would go to a cause*

Sabrina defends her project by 'explaining away' the criticism with a hypothetical purpose (to promote) of the waste bin. In this case, the form of the solution is a process - 'half of our proceeds would go to a cause' - rather than a 'thing'. Note also that Sabrina provides a theory that could prove the validity of her hypothesis of the Tidy Tumbler as 'promotional thing for a waste management': 'everyone loves to give back'. Therefore, a deductive proof that the Tidy Tumbler would be something that 'everyone loves' is based on the rule that 'things that give back are loved by everyone'.

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 DTRS 10 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 that require deductive reasoning from established rules has been recognized as a crucial part of this task.

Although design evaluation in its strictest sense should only entail deductive logic (p0q Something with quality should be selected; p This concept has quality; rq This concept should be selected.), this dataset demonstrates that the design evaluation of not-yet-fully-elaborated concepts was not strictly deductive or abductive. Design evaluations neither ended with a conclusion nor proposed new actions without being grounded in a conclusion drawn from the current evidence. Rather, concept evaluations exhibited a pattern in which deductive analysis of available evidence based upon established criteria led to and coincided with new abductive hypotheses, as shown in the Deduction Present and Abduction Present cell of Table 5. These new hypotheses could be tested using deductive analysis.

The known patterns of design thinking during concept evaluation as being about assessing the merits of a concept as it stands or about pruning away inferior options (Liu et al., 2003) do not fully describe this pattern exhibited in the design review conversations analysed. While instances of deductive and abductive logic occurred independently, the novel pattern of interest is when abduction was deployed to explain the concept evaluation:

q	a given:	concept evaluation
$p \Rightarrow q$	first conclusion:	IF *new inference* THEN concept evaluation
p	second conclusion:	*new inference*

In these instances, design evaluations contained a recursive loop in which new propositions are invented as a means to explain the evaluation, but these propositions become tested. We define this pattern as generative sensing, a process of creating new hypotheses to explain, resolve, or challenge the evidence in favour of or against a design concept, evidence that was itself generated from an evaluation of the design concept. In the context of design evaluation, abduction entails inferences to explain the concept evaluation. The pattern of generative sensing is depicted in the following diagram, Figure 1.

Todd's chair and Adam's bench cases described previously illustrate this pattern of a recursive cycle of generating a series of tests about concepts until an appropriate concept is identified. These inferences may provide resolutions to problems identified by the evaluation when the evaluation is adverse. This is the situation encountered in Todd's design process. The vertical text depicts evidence (e.g. 'it might not be comfortable') used to lead to the conclusion shown at the end of the arrow (e.g. 'So what you have here it shows them sagged'). The lines at an angle point to the desired value (e.g. 'I think the challenge is how do you connect them all.') for the abduction (e.g. 'If there was some sort of interconnection where you could actually pull that out'). The evaluation that Todd's original concept could not, as desired, transform into different seating configurations, eventually led to a final concept using a 'lazy Susan' as the method of transformation. Figure 2 depicts the generative sensing that occurred throughout Todd's design process. During each design review session with the design coaches, evaluations of Todd's concept led to inferences that could produce the intended outcomes.

In contrast, a positive evaluation may spur the proposition of conditions that would undermine the basis of the evaluation in order to test the robustness of the evaluation. This is the situation encountered in the case of the evaluation

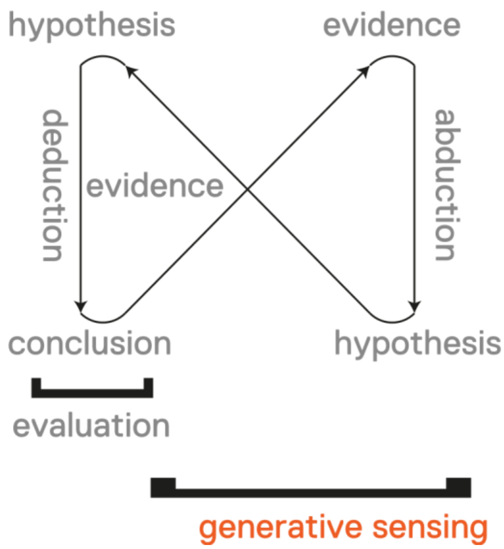
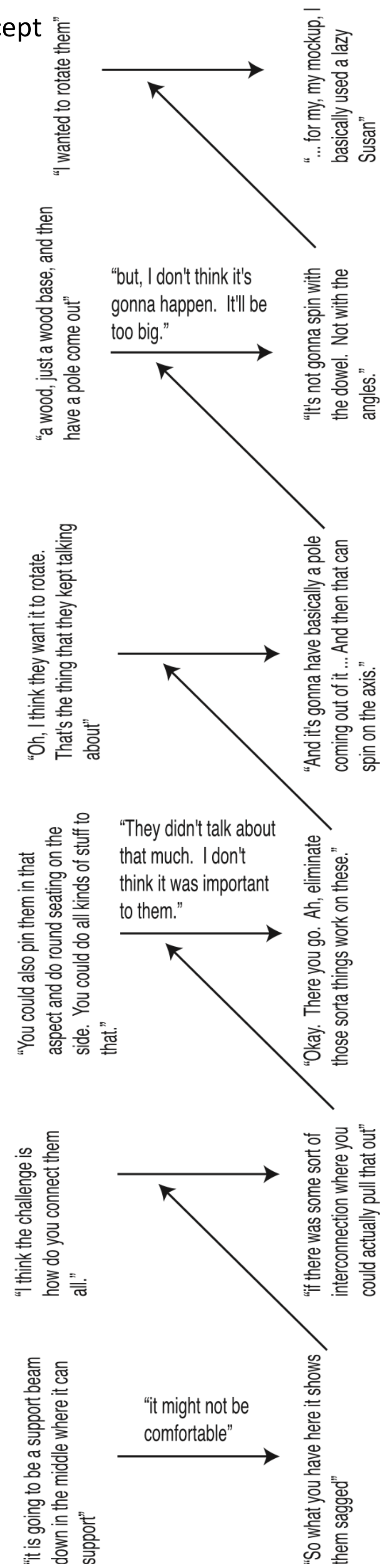


Figure 1 Generative sensing

as a pattern of design thinking

Figure 2 Generative sensing sequence for Todd’s seating concept



of Adam's bench. In the situation in which the new hypotheses challenge the evaluation, then the abduction negates the observation, e.g., THEN NOT concept evaluation. In other words, the inference of having Adam's bench up against the wall negates the positive concept evaluation.

The 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 scheme based upon a value judgement for generating potential solutions. The value judgement, which does not satisfy all constraints, provides 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 concept. Thus, rather than a 'way in to the problem', generative sensing can be seen as creating alternative 'ways through the problem'.

Driving the transition between each recursive loop are innovative abductions. Notably, the results illustrate that innovative abduction does not necessarily start or end with function and form as endpoints. The situation may be that the direction of the innovative abduction is more related to both divergent and 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: individuals make sense of apparently disconnected facts that they 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, Kramer, 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 the innovativeness of new products or services. By contrast, deductive reasoning and convergent thinking led to a single conventional answer rather than a range of creative, unconventional means-ends relations.

Our results suggest that the direction of abduction is not likely to be simply divergent or convergent. Rather, abductive reasoning can be directed toward both divergent and convergent thinking. In the former, it creates inferences about new possible use contexts or a new function, for example, that could be explored. 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), such as when the inference of a new interconnection changed Max's framing of Todd's modular seating into a chair. For the latter, generative sensing infers new forms that resolve identified problems to converge toward 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 converging pathway to a workable solution.

McDonnell (2015) and Adams, Forin, Chua, and Radcliffe (2015) present alternative interpretations to our claim that generative sensing is used to resolve problems and to question the basis of a concept. 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 critiques, which we would have coded as inferences to changed forms or changed behaviours, are neither intended to be acted upon nor performative. Rather, the critiques operate as rhetorical instruments. The concepts (artifacts) are rhetorical devices to enable students to convey justifications for their 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 decisions rather than to prescribe courses of action. Thus, a function of generative sensing may be to test a 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 Looks Like review summarises 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 (2015) analysed the structure of the mechanical engineering design course according to Basil Bernstein's concept of framing (2000). Framing is 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; when the student controls them, the framing is considered weak. Wolmarans noted that 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, discipline, or way of designing; hence, it is possible to conclude that the framing is 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 a student's commitment to the design concept.

Abduction is a type of cognitive process associated with reasoning. Abduction in turn is supported by other cognitive processes, such as mental simulation. Christensen and Ball (2015) 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 the 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). 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. These were coded as instances of Modifying or introducing a new form for the concept (AB). The overlap in codes would suggest that abduction, and therefore generative sensing, relies on the cognitive process of mental simulation (Christensen & Schunn, 2009).

Conclusions

In this study, we have illustrated that design review conversations consist of two components: deductive analysis of existing evidence and abductive reasoning explaining conclusions raised by the deductive analysis. When these co-occur in a recursive process, we call the process generative sensing. Abductive hypotheses included proposed structural changes, behavioural (mode of operation) modifications, product framing, modes of user operation, or contexts of use that could either resolve a problem or undermine the logic of the present design concept.

The question raised in this research is whether it is appropriate that design evaluation, even in its strictest 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 they do. 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 designers only look at what they have, they may not see what they could have.

The recursive pattern of generative sensing presents an attractive model of design thinking that can help aspiring entrepreneurs and managers alike form capabilities to avoid premature commitment to a single answer (the outcome of deductive reasoning). On the 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 entrepreneurs 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 one makes us comfortable. On the other hand, innovators have a natural tendency to move against the status quo, taking advantage of any occasion to question it and generate opportunities to improve it (Dyer, Gregersen, & Christensen, 2008). Helping designers and entrepreneurs to develop generative sensing skills is likely to encourage them to look beyond the familiar toward innovation and fresh ideas. By hypothesising new possibilities, designers and entrepreneurs may discover new innovations when seeking to affirm the consequent stated in the abductive hypothesis.

References

Adams, R. S. (2015). Design review conversations: the dataset. In R. S. Adams, & J. A. Siddiqui (Eds.), Analyzing Design Review Conversations (pp. 23e30). West Lafayette, IN: Purdue University Press.

Adams, R. S., Forin, T., Chua, M., & Radcliffe, D. (2015). Making visible the “how” and “what” of design teaching. In R. S. Adams, & J. A. Siddiqui (Eds.), Analyzing Design Review Conversations (pp. 431e456). West Lafayette, IN: Purdue University Press.

Austen, H. (2012). The open mind: letting go of single-answer certainty. Rotman Management Winter 58e64.

Bardolet, D., Fox, C. R., & Lovallo, D. (2011). Corporate capital allocation: a behavioral perspective. Strategic Management Journal, 32(13), 1465e1483.

Berns, G. (2008). Iconoclast: A Neuroscientist Reveals How to Think Differently. Boston: Harvard Business Press.

Bernstein, B. (2000). Pedagogy, Symbolic Control, and Identity: Theory, Research, Critique. Revised ed.. In: Critical Perspectives Series. Oxford: Rowman & Littlefield

Christensen, B. T., & Ball, L. J. (2015). Dimensions of creative evaluation: distinct design and reasoning strategies for aesthetic, functional and originality judgments. In R. S. Adams, & J. A. Siddiqui (Eds.), Analyzing Design Review Conversations (pp. 115e134). West Lafayette, IN: Purdue University Press.

Christensen, B. T., & Schunn, C. D. (2009). The role and impact of mental simulation in design. Applied Cognitive Psychology, 23(3), 327e344.

Clark, C. (2008). The impact of entrepreneurs’ oral ‘pitch’ presentation skills on business angels’ initial screening investment decisions. Venture Capital: An International Journal of Entrepreneurial Finance, 10(3), 257e279.

Cropley, A. (2006). In praise of convergent thinking. Creativity Research Journal, 18(3), 391e404.

Darke, J. (1979). The primary generator and the design process. Design Studies, 1(1), 36e44.

Dimov, D. (2007). From opportunity insight to opportunity intention: the importance of person-situation learning match. Entrepreneurship Theory and Practice, 31(4), 561e583.

Dong, A., Kleinsmann, M., & Valkenburg, R. (2009). Affect-in-cognition through the language of appraisals. Design Studies, 30(2), 138e153.

Dong, A., Lovallo, D., & Mounarath, R. (2015). The effect of abductive reasoning on concept selection decisions. Design Studies, 37, 37e58.

Dorst, K. (2011). The core of ‘design thinking’ and its application. Design Studies, 32(6), 521e532.

Dorst, K., & Cross, N. (2001). Creativity in the design process: co-evolution of problem-solution. Design Studies, 22(5), 425e437.

Dyer, J. H., Gregersen, H. B., & Christensen, C. (2008). Entrepreneur behaviors, opportunity recognition, and the origins of innovative ventures. Strategic Entrepreneurship Journal, 2(4), 317e338.

Dym, C. L., Wood, W. H., & Scott, M. J. (2002). Rank ordering engineering designs: pairwise comparison charts and borda counts. Research in Engineering Design, 13(4), 236e242.

Eisenhardt, K. M. (1989). Building theories from case study research. The Academy of Management Journal, 14(4), 532e550.

Finke, R. A. (1995). Creative insight and preinventive forms. In R. J. Sternberg (Ed.), The Nature of Insight (pp. 255e280). Cambridge, MA: MIT Press.

Finke, R. A. (1996). Imagery, creativity, and emergent structure. Consciousness and Cognition, 5(3), 381e393.

Fredrickson, J. W., & Mitchell, T. R. (1984). Strategic decision processes: comprehensiveness and performance in an industry with an unstable environment. Academy of Management Journal, 27(2), 399e423.

Frey, D., Herder, P., Wijnia, Y., Subrahmanian, E., Katsikopoulos, K., & Clausing, D. (2009). The pugh controlled convergence method: model-based evaluation and implications for design theory. Research in Engineering Design, 20(1), 41e58.

Friedman, B., & Kahn, P. H., Jr. (2003). Human values, ethics, and design. In A. Sears, & J. A. Jacko (Eds.), The Human-computer Interaction Handbook: Fundamentals, Evolving Technologies and Emerging Applications (2nd ed.). (pp. 1177e1201) L. Erlbaum Associates Inc.

Galle, P. (1996). Design rationalization and the logic of design: a case study. Design Studies, 17(3), 253e275.

Garbuio, M., Lovallo, D., & Sibony, O. (2015). Evidence doesn't argue for itself: the value of disinterested dialogue in strategic decision making. Long Range Planning, 48(6), 361e380.

Gavetti, G. (2012). PERSPECTIVE - toward a behavioral theory of strategy. Organization Science, 23(1), 267e285.

Gero, J. S., & Kannengiesser, U. (2004). The situated functionebehaviourestructure framework. Design Studies, 25(4), 373e391.

Gielnik, M. M., Kr€amer, A.-C., Kappel, B., & Frese, M. (2014). Antecedents of business opportunity identification and innovation: Investigating the interplay of information processing and information acquisition. Applied Psychology, 63(2), 344e381.

Govindarajan, V., & Trimble, C. (2010). The Other Side of Innovation: Solving the Execution Challenge. Cambridge: Harvard Business School Publishing.

Hayes, A. F., & Krippendorff, K. (2007). Answering the call for a standard reliability measure for coding data. Communication Methods and Measures, 1(1), 77e89.
Kelley, T., & Littman, J. (2001). The Art of Innovation: Lessons in Creativity from IDEO. New York: America's Leading Design Firm. Currency/Doubleday.
Kolko, J. (2010). Abductive thinking and sensemaking: the drivers of design synthesis. Design Issues, 26(1), 15e28.
Kroll, E., & Koskela, L. (2014). On abduction in design. In J. S. Gero, & S. Hanna (Eds.), Design Computing and Cognition DCC14 (pp. 357e376). Dordrecht: Springer.
Lande, M., & Oplinger, J. (2014). Disciplinary discourse in design reviews: Industrial design and mechanical engineering courses. In Proceedings of DTRS 10 Symposium. West Lafayette, IN: Purdue University.
Le Dantec, C., & Do, E. Y.-L. (2009). The mechanisms of value transfer in design meetings. In J. McDonnell, & P. Lloyd (Eds.), About: Designing - Analysing Design Meetings (pp. 101e118). London: CRC Press.
Leonard, D., & Sensiper, S. (1998). The role of tacit knowledge in group innovation. California Management Review, 40(3), 112e132.
Levinthal, D. A. (1997). Adaptation on rugged landscapes. Management Science, 43(7), 934e950.
Liu, Y.-C., Chakrabarti, A., & Bligh, T. (2003). Towards an 'ideal' approach for concept generation. Design Studies, 24(4), 341e355.
Lloyd, P. (2009). Ethical imagination and design. Design Studies, 30(2), 154e168.
Lombard, M., Snyder-Duch, J., & Bracken, C. C. (2002). Content analysis in mass communication: assessment and reporting of intercoder reliability. Human Communication Research, 28(4), 587e604.
Malak, J. R. J., & Paredis, C. J. J. (2010). Using parameterized pareto sets to model design concepts. Journal of Mechanical Design, 132(4). http://dx.doi.org/10.1115/1.4001345. 041007e041007.
March, J. G. (1991). Exploration and exploitation in organizational learning. Organization Science, 2(1), 71e87.
McDonnell, J. (2015). Becoming a designer: some contributions of design reviews. In R. S. Adams, & J. A. Siddiqui (Eds.), Analyzing Design Review Conversations (pp. 355e372). West Lafayette, IN: Purdue University Press.
Mumford, M. D. (2003). Where have we been, where are we going? Taking stock in creativity research. Creativity Research Journal, 15(2e3), 107e120.
Nelson, B. A., Wilson, J. O., Rosen, D., & Yen, J. (2009). Refined metrics for measuring ideation effectiveness. Design Studies, 30(6), 737e743.
Nikander, J. B., Liikkanen, L. A., & Laakso, M. (2014). The preference effect in design concept evaluation. Design Studies, 35(5), 473e499.

Oman, S. K., Tumer, I. Y., Wood, K., & Seepersad, C. (2013). A comparison of creativity and innovation metrics and sample validation through in-class design projects. Research in Engineering Design, 24(1), 65e92.

Papadakis, V. M., & Barwise, P. (2002). How much do CEOs and top managers matter in strategic decision-making? British Journal of Management, 13(1), 83e95.

Pugh, S. (1981). Concept selection: a method that works. In V. Hubka (Ed.), International Conference on Engineering Design. Vol. WDK 5: Design Methodology: Review of Design Methodology - ICED 81 (pp. 497e506). Rome, Italy: Heurista.

Roozenburg, N. (1993). On the pattern of reasoning in innovative design. Design Studies, 14(1), 4e18.

Saunders, M. N., Seepersad, C. C., & Holtta-Otto, K. (2011). The characteristics of innovative, mechanical products. Journal of Mechanical Design, 133(2). 021009e9.

Scott, M. J., & Antonsson, E. K. (1998). Aggregation functions for engineering design trade-offs. Fuzzy Sets and Systems, 99(3), 253e264.

Shah, J. J., Smith, S. M., & Vargas-Hernandez, N. (2003). Metrics for measuring ideation effectiveness. Design Studies, 24(2), 111e134.

Sullivan, L. H. (1896). The tall office building artistically considered. Lippincott's Magazine 403e409.

Thurston, D. L. (1991). A formal method for subjective design evaluation with multiple attributes. Research in Engineering Design, 3(2), 105e122.

Ulrich, K. T., & Eppinger, S. D. (2004). Product Design and Development (3rd ed.). New York: McGraw-Hill/Irwin.

Verhaegen, P.-A., Vandevenne, D., Peeters, J., & Duflou, J. R. (2013). Refinements to the variety metric for idea evaluation. Design Studies, 34(2), 243e263.

Ward, T. B. (2007). Creative cognition as a window on creativity. Methods, 42(1), 28e37.

Welling, H. (2007). Four mental operations in creative cognition: the importance of abstraction. Creativity Research Journal, 19(2e3), 163e177.

Wolmarans, N. (2015). Navigating boundaries: moving between context and disciplinary knowledge when learning to design. In R. S. Adams, & J. A. Siddiqui (Eds.), Analyzing Design Review Conversations (pp. 97e114). West Lafayette, IN: Purdue University Press.

Yilmaz, S., & Daly, S. R. (2015). Directing convergent and divergent activity through design feedback. In R. S. Adams, & J. A. Siddiqui (Eds.), Analyzing Design Review Conversations (pp. 413e430). West Lafayette, IN: Purdue University Press.

Zeng, Y., & Cheng, G. D. (1991). On the logic of design. Design Studies, 12(3), 137e141.