Design Principles: Literature Review, Analysis, and Future Directions

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Design principles are created to codify and formalize design knowledge so that innovative, archival practices may be communicated and used to advance design science and solve future design problems, especially the pinnacle, wicked, and grand-challenge problems that face the world and cross-cutting markets. Principles are part of a family of knowledge explication, which also include guidelines, heuristics, rules of thumb, and strategic constructs. Definitions of a range of explications are explored from a number of seminal papers. Based on this analysis, the authors pose formalized definitions for the three most prevalent terms in the literature—principles, guidelines, and heuristics—and draw more definitive distinctions between the terms. Current research methods and practices with design principles are categorized and characterized. We further explore research methodologies, validation approaches, semantic principle composition through computational analysis, and a proposed formal approach to articulating principles. In analyzing the methodology for discovering, deriving, formulating, and validating design principles, the goal is to understand and advance the theoretical basis of design, the foundations of new tools and techniques, and the complex systems of the future. Suggestions for the future of design principles research methodology for added rigor and repeatability are proposed. [DOI: 10.1115/1.4034105]

1 Introduction

A number of technical research fields have grown and matured over decades through the investigation, study, experimentation, and validation of core principles. Accepted research methodologies and standards similarly emerge and mature, founded on the scientific method, but also tailored to the characteristics and scope of the field. The life sciences and physical sciences are classical examples of this growth and maturation process. Numerous cases are prevalent in these fields, such as the theories and laws of classical mechanics to explain the motion of particles, bodies, and systems of bodies.

Design research, or design science, is a relatively young field of research investigation. With the first treatises published around the mid-20th century, the depth of investigation of, public awareness of, and resources devoted to design science has grown steadily [1]. From the very earliest discourse related to this field, like in Glegg's "The design of design," principles of design have been postulated [2]. Because of the broad, interdisciplinary or transdisciplinary nature of design science, numerous forms of design principles have been suggested across disciplines, among disciplines, and at various levels of granularity/specificity. Now it is time to carefully study these efforts and seek a formalization of design principles, definitions, and supporting research methodologies.

In this paper, we seek to make strides in formalizing design principles from various disparate theoretical, empirical, and experimental approaches, and draw more defined distinctions among the terms commonly used in the literature. This research will assist in enabling a fundamental understanding and development of design principles and associated processes. In addition, we hope it will guide researchers and practitioners in the advancement and use of such principles. Ultimately, the research provides a foundation for design science. This paper builds on earlier work presented by the authors [3].

Contributed by the Design Theory and Methodology Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received November 3, 2015; final manuscript received June 13, 2016; published online August 30, 2016. Assoc. Editor: Mathew I. Campbell.

2 Background

The formalization of design *research* methodology (DRM) is the indisputable path to the maturation of the field. Pahl and Beitz were some of the first to propose formalized design processes and research [4]. Blessing and Chakrabarti formulated a DRM process comprising of four main steps: (1) Research Clarification, literature review to formulate a worthwhile research goal, (2) Descriptive Study I, empirical data analysis in an exploratory study, (3) Prescriptive Study, experience synthesized into a vision of how to improve upon on the existing situation, and (4) Descriptive Study II, empirical data analysis of the effect of the improvement support developed [5]. Finger and Dixon extensively reviewed design research methods, including descriptive models of design processes, prescriptive models for design, computer-based models of design processes, languages, representations, and environments for design, analysis to support design decisions, design for manufacturing and other life cycle issues like reliability, serviceability, etc. [6,7]. Many of the research efforts reviewed in this paper fall into one of these categories, whether *descriptive models*, like case studies, protocol studies, and observations, or *prescriptive models* of how the design process ought to be carried out [7]. Inductive versus deductive research methodologies are a particular focus in this paper. Inductive research is based upon a process in which data are collected first, patterns are extracted, and a theory is developed to explain those patterns. Deductive research is based upon a process in which a theory is developed first, after which data are collected and analyzed to determine if the theory is supported. Though not perfectly aligned in meaning, descriptive and inductive research methods are similar in that they both rely on discovery of patterns and findings in data. Prescriptive and deductive research methods are similar in that they pose a theoretical solution or answer, and test if it is effective or supported. The methodologies reviewed in this paper tend to fit into one of these two categories, though some are in both. In reviewing the current research efforts to extract design principles, effective techniques and areas for improvement or the development of greater rigor can be identified toward a more formalized design principles research methodology.

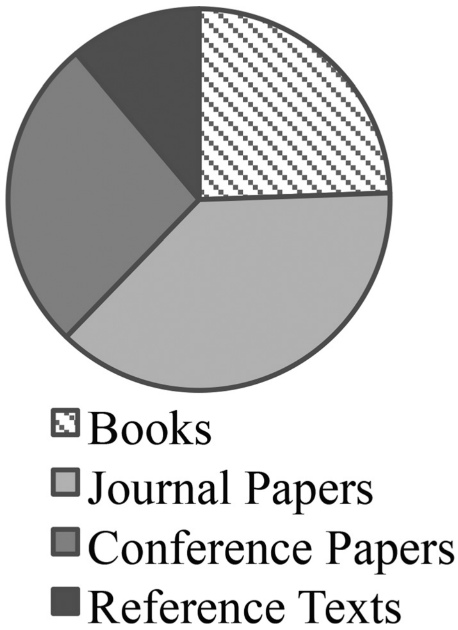

Fig. 1 Proportion of reference types

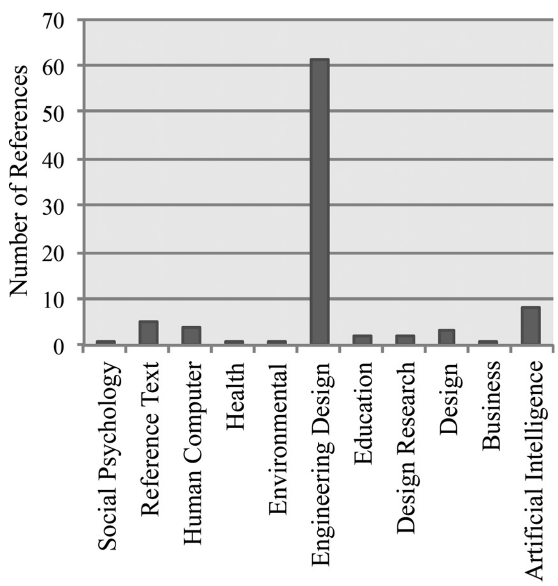

Fig. 2 Field of references

3 Research Methodology

This paper is both a literature review and an original critical analysis of the state of the art, with the goal of advancing and formalizing the field of design principles research. To gain an understanding of the types and prevalence of each type of methodology for exploring, deriving, and validating design principles, the authors reviewed 66 sources. These included monographs, books, anthologies, journal publications, and conference publications. References were chosen based on either their seminal nature to the foundation of the field (noted by their longevity and/or high citation rate) or their publication in leading design engineering journals or conference proceedings. Figures 1–3 show the proportional breakdown of types of references, the field that the references come from, and the distribution of references by year of publication.

As each reference was reviewed, the authors tabulated the following information from each source where applicable: keywords/key topics, main contribution/brief synopsis, methods to find principles, methods to validate principles, principles discovered, and any articulated formal nomenclature definitions. These data were analyzed in several different ways, as reviewed in Secs. 4, 5, and 6.

4 Discussion of Nomenclature

In the pursuit of standardization, formalization, and added rigor to any scientific methodological undertaking, the articulation of clear and well-reasoned definitions for key concepts is imperative. Formal definitions ensure a common understanding and universal language, not only between the authors and readers but also throughout the research community. In the following Secs. 4.1–4.4, the authors articulate formal definitions of design principles from the literature reviewed. A formal definition for each term is then posed based on an aggregate assessment of the literature findings and the expertise of the authors. These definitions are within the context of the design research field, and therefore, have an implied "design" before each term reviewed (i.e., *design* principle).

4.1 Principle. Design principles are the focus of this research, though the methodologies surrounding their conceptual kin (i.e., heuristics, etc.) can be and often are similar, relevant, and applicable to those for design principles. Several definitions and characteristics have been gathered and juxtaposed below in their original form. Researchers use a large variety of terms when defining *principle*, including technique, methodology, data, experience, example, recommendation, suggestion, assertion, and proposition. Factors considered when classifying and describing principles include the level of detail in which they impact the design, the point of application in the design process, the level of

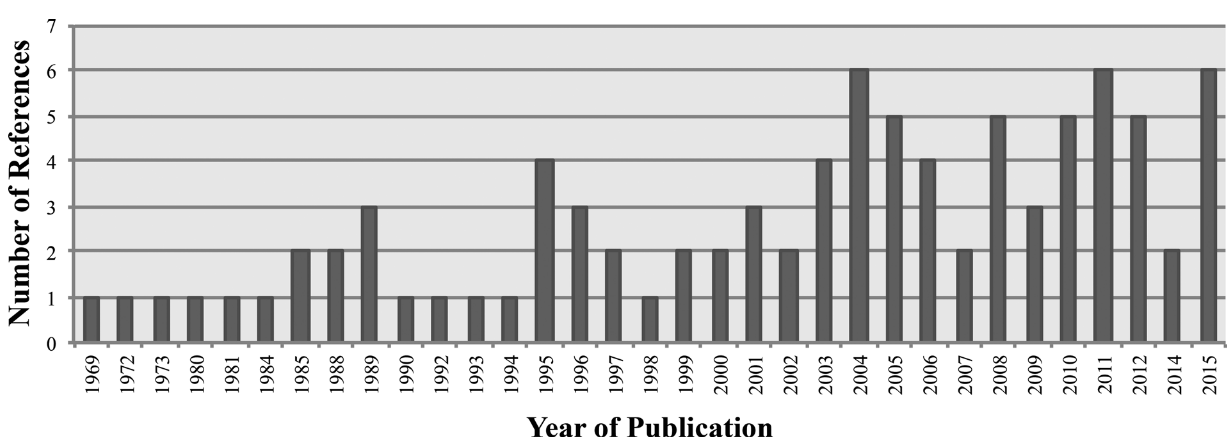

Fig. 3 Reference year of publication

abstraction, the specificity or granularity of the principle itself, the manner in which principle is applied, and the level of refinement or success of the principle, among others. As expected, terms like *guideline* are used to define principles, and are often used interchangeably in informal settings. The term *ontology* is related to *principle*, in that it is "an explicit specification of a conceptualization…" [8]. Often, ontologies are developed as the formal, consistent language with which to express design knowledge codification. To summarize the literature review in Table 1, the common threads that can be observed throughout most of the definitions are:

- Principles are not universally applicable, effective, or true, but instead are generally applicable, effective, and true in a given context.
- Principles are typically based on experiences, examples, or empirical evidence.
- The application of principles may be context and/or problem dependent, but should be more generalizable than a few isolated instances.
- Principles are used as foundations for understanding and for the development of supporting methods, techniques, and tools.

Based on the literature review and analysis of the definitions, the following is a proposed formal definition for *principle*.

Formal Definition:

Principle: A fundamental rule or law, derived inductively from extensive experience and/or empirical evidence, which provides design process guidance to increase the chance of reaching a successful solution.

Table 1 Literature review of definitions and characteristics for "principle"

Source	Definition/characteristics
Merriam-Webster dictionary [9]	"A moral rule or belief that helps you know what is right and wrong and that influences your actions; a basic truth or theory: an idea that forms the basis of something; a law or fact of nature that explains how something works or why something happens"
Moe et al. [10] Weaver et al. [11] Singh et al. [12]	"A (transformation) principle is a *generalized directive* to bring about a certain type of mechanical transformation. A (transformation) principle is a *guideline* that, when embodied, singly creates a transformation."
Glegg [2]	"Principles of engineering design can be divided into *three distinct types*: *(1) Specialized techniques*: *particular data* and *manufacturing techniques* that have been amassed over a long period of time with respect to a very specific technology that you cannot hope to design that product without—i.e., camshaft for a petrol engine. *(2) General rules*: *broader theoretical considerations* which are not confined to a single engineering mechanism—wide though their scope may be, they are not of universal application. *(3) Universal principles*: *underlying laws* which *cross* the *frontiers* of most *engineering design*. They are the rules behind the rules; they are not tied to any particular type of design, they concern the design of design."
Bell et al. [13]	Design principles are "…an *intermediate step* between *scientific findings*, which must be generalized and replicable, and *local experiences* or *examples* that come up in practice. Because of the need to interpret design principles, they are not as readily falsifiable as scientific laws. The principles are *generated inductively* from *prior examples* of *success* and are subject to *refinement* over time as others try to adapt them to their own experiences. In this sense, they are falsifiable; if they do not yield purchase in the design process, they will be debated, altered, and eventually dropped."
Kali [14]	"*Specific principles* describe the *rationale* behind the design of a *single feature or single research investigation*. Due to their direct relation to one feature, specific principles in the database are embedded within the features. *Pragmatic principles connect* several specific principles (or several features),… *Metaprinciples* capture *abstract ideas* represented in a cluster of pragmatic principles."
Anastas and Zimmerman [15]	"The principles are not simply a listing of goals, but rather a *set* of *methodologies* to *accomplish* the *goals*…the breadth of the principles' *applicability* is important. When dealing with design architecture,…the same…principles must *be applicable, effective, and appropriate*. Otherwise, these would not be principles but simply a list of useful techniques that have been successfully demonstrated under specific conditions. Just as every parameter in a system *cannot be optimized at any one time*, especially when they are interdependent, the same is true of these principles. There are cases of synergy in which the successful application of one principle advances one or more of the others."
Mattson and Wood [16]	"A principle…[is] a *fundamental proposition* used to *guide* the *design process*. The principles in this paper are not suggestions or activities the designer should complete, they are assertions that can guide the designer to a *more effective outcome*. The principles do not explicitly say what should be done; they simply *guide* the engineer *as decisions are made*…although principles are *not guaranteed*, and at times they *should not be followed*, they should *always be considered*"
McAdams [17]	A design principle is "'a *recommendation* or *suggestion* for a *course of action* to *help solve a design issue*.' This definition is adapted from the definition for a design *guideline* according to Ref. [23]. *Off-line principles* are applied at the *design stage*. *On-line principles* are applied *anytime after this stage*, including manufacturing and during use. Another characteristic that distinguishes between the principles is the *level of detail* that they change the design."
Perez et al. [18]	"A set of principles can make this process *more efficient* as well as *improve on the design* of the original product. The principles provide a means of *processing the information* gathered in the reverse engineering step in order to *derive ideas based on specific details encompassed by the example products*."
Sobek et al. [19]	"…Principles…are *not steps, prescriptions, or recipes*. Rather, (Toyota chief) engineers *apply* the principles to *each design project differently*. Design engineers use the principles to *develop and evaluate a design process*. The key to success is the implementation of ideas as much as the principles themselves."
Altshuller [20]	"Technical evolution has its own *characteristics* and *laws*. This is why different inventors in different countries, working on the same technical problems independently, come up with the same answer. This means that certain *regularities* exist. If we can find these regularities, then we can use them to solve technical problems—*by rules, with formulae*, without wasting time on sorting out variants."—In describing the 40 inventive principles of TRIZ
Pahl and Beitz [4]	"Only the combination of the physical effect with the geometric and material characteristics (working surfaces, working motions and materials) allows the principle of the solution to emerge. This interrelationship is called the *working principle*…and it is the *first concrete step* in the *implementation* of the *solution*."

Table 2 Literature review of definitions for "guideline"

Source	Definition/characteristics
Merriam-Webster Dictionary [21]	"A rule or instruction that shows or tells how something should be done"
Greer et al. [22]	"Design guidelines provide a *means* to *store* and *reuse design knowledge* with the potential to be effective in the *early stages* of design where…*broad knowledge* is *beneficial*. The format used to present the product evolution design guidelines is the *imperative form* from English grammar…according to Nowack, a design guideline has at least four parts: issue(s) addressed or impacted, links to design context, action recommendations, and rationale [23]."
Nowack [23]	A design guideline is "a *prescriptive recommendation* for a *context sensitive course of action* to *address a design issue*."
Kim [24]	"…Design guidelines can…be considered as an *intermediary interface* between the *designer* and…[expert] *knowledge*. The purpose of design guidelines is to *enable designers* to make *usable* and *consistent applications* that *conform* to *designated conventions*. To maximize the compliance of the resulting products, it is important to produce design guidelines that *designers can actually understand and apply* [25]. Design guidelines address a wide *range* of *design levels*; the contents are typically based on *laboratory experiments* and *experts' opinions*. These guidelines are being *continuously revised* and *updated* to meet technical and environmental *changes*."
Bevan and Spinhof [26]	"A good set of guidelines is composed of a *combination* of more *specific* guidelines for the *application* at hand and more *generic* guidelines that refer to more *general aspects*…" "And the set of guidelines should be *well documented*, including *good or bad examples*, a thorough table of contents and glossaries [24]."
Jaünsch and Birkhofer [27]	"The *generality* inherent in all guidelines has been greatly increased… direction of the guidelines has changed from a personal support for individuals…toward a *general procedure* for a *company* addressing organization and content….advice within the guidelines [has] changed from addressing concrete thinking processes to *general problem solving advice*…instructions have changed from statements that can be immediately put into action or thought to *instruction on an abstract level*, which *need to be adapted to the current situation* of the designer… appearance of the descriptions of the guidelines have altered from a pure one-page text-based description to comprehensive descriptions with *figures*, in particular *flow charts and in-depth texts*….content of the descriptions has been enhanced with *figures*, *examples* and a *quantity* of *text*."
Matthews [28]	"Guidelines can provide *additional assistance* by *predicting likely outcomes* of *actions* and by *identifying additional issues* that should be *considered*. For guideline support to be effective, appropriate guidelines must be available to the designer at the *time of a design decision*."

Example Principle: "Transformational Principle No. 1: Expand/Collapse. Change the physical dimensions of an object to bring about an increase/decrease in occupied volume primarily along an axis, in a plane or in three dimensions." [12]

4.2 Guideline. As discovered in the literature addressing the definitions and characteristics of principles, we find similar content for definitions and characteristics of guidelines. Key terms found throughout the literature quoted in Table 2 include prescriptive, imperative, advice, instruction, opinion, recommendation, assistance, prediction, and general. Descriptions address factors like when to use guidelines during the design process, how they must be changed and revised, and how they must be presented to the user. There are key differences that stand out between the definitions of principles and guidelines:

- Guidelines are generally presented as more context dependent and changeable than principles—perhaps even less "universal" or "fundamental."
- The literature on guidelines places strong emphasis on their modality, organization, and level of detail of presentation for maximum effectiveness and usability, though this could be an artifact of the choice of references.
- Guidelines are described as more prescriptive than heuristics, presented in Sec. 4.3, which tend to be descriptive *or* prescriptive.

Based on the literature review and analysis of the definitions, the following is a proposed formal definition for *guideline*.

Formal Definition:

Guideline: A context-dependent directive, based on extensive experience and/or empirical evidence, which provides design process direction to increase the chance of reaching a successful solution.

Example Guideline: "Minimiz[e] the quantity of resource use by optimizing its rate and duration." [29]

4.3 Heuristic. The term heuristic has an understandably broader and richer base of literature from which its definition can be derived, as it has both connotations with computational applications and noncomputational design process applications. Table 3 draws upon both sets (computational and cognitive) of literature in an attempt to generalize the definition among the fields of application. Key terms used in describing and defining heuristics from the sampled literature include rule of thumb, guideline, common sense, principle, experience, observation, knowledge, lesson, strategy, simple, concise. Again, as in Secs. 4.1 and 4.2 defining principle and guideline, we find the terms can be and often are used interchangeably in the literature. Distinctions that emerge based on the literature sampled that make heuristics unique include:

- Emphasis on reducing search time—not necessarily an optimal result, but satisfactory, practical, or "quick and dirty."
- Ability to be prescriptive *or* descriptive, unlike guidelines, which are mostly prescriptive.
- Value is typically defined by usefulness.
- Heuristics are generally reliable, but potentially fallible depending on context and circumstances.
- There may not be as extensive evidence or validation of heuristics, compared to guidelines and especially compared to principles.

Based on the literature review in Table 3 and analysis of these definitions, the following is a proposed formalized definition for *heuristic*.

Formal Definition:

Heuristic: *A context-dependent directive, based on intuition, tacit knowledge, or experiential understanding, which provides design process direction to increase the chance of reaching a satisfactory but not necessarily optimal solution.*

Example Heuristic: "A properly designed bolt should have at least one and one-half turns in the threads." [38]

The main differences between heuristics and guidelines are:

- Guidelines can be based on empirical evidence, whereas heuristics are generally not.
- Heuristics increase your chances of reaching a successful but not (necessarily) optimal solution whereas guidelines do not have specific attributes regarding "level" of success.

Table 3 Literature review of definitions for "heuristic"

Source	Definition/characteristics
Merriam-Webster Dictionary [30]	"Using experience to learn and improve; involving or serving as an aid to learning, discovery, or problem-solving by experimental and especially trial-and-error methods <*heuristic* techniques> <a *heuristic* assumption>; *also*: of or relating to exploratory problem-solving techniques that utilize self-educating techniques (as the evaluation of feedback) to improve performance <a *heuristic* computer program>"
Stone and Wood [31]	"(Module) heuristics: A method of examination in which the designer uses *a set of steps, empirical in nature, yet proven scientifically valid*, to identify (modules) in a design problem. This definition requires another: the phrase "*proven scientifically valid*" refers to a hypothesis, formulated after systematic, objective data collection that has *successfully passed* its *empirical tests*. Thus, the *heuristics* are *proven* by following the *scientific method*."
Bolc and Cytowshi [32]	"Heuristics [are] *explicit rules* derived from *human experiences* and *tacit knowledge*."
Li et al. [33]	"Heuristics are *rules-of-thumb* that have been successful in producing "*acceptable*," *not necessarily* "*optimal" solution* to a type of problem."
Chong et al. [34]	Heuristics "…are *criteria, methods*, or *principles* for *deciding* which *among several alternative courses* of *action promises* to be the *most effective* in order to *achieve the desired goals*."
Nisbett and Ross [35]	"Heuristics are *reasoning processes* that *do not guarantee the best solution*, but *often lead to potential solutions* by providing a *"short-cut"* within cognitive processing."
Pearl [36]	"The term "heuristic" has commonly referred to *strategies* that *make use of readily accessible information* to *guide problem-solving*."
Yilmaz and Seifert [37]	"The term heuristic implies that it: (1) *Does not guarantee reaching the best solution*, or *even a solution*; and (2) *Provides* a *"quick and dirty" (easier) method* that often leads to an *acceptable solution*."
Koen [38]	"*All engineering is heuristic*. "*Synonyms* of the heuristic: rule of thumb, intuition, technique, hint, aid, direction, rule of craft, engineering judgment, working bias, random suggestions, le pif (the nose)" A heuristic is an "*engineering strategy* for causing *desirable change* in an *unknown* situation within the *available resources*…anything that provides a *plausible aid* or *direction* in the solution of a problem but is in the final analysis *unjustified*, *incapable* of *justification*, and *fallible*. It is used to *guide*, to *discover*, and to *reveal*." "Signatures of the heuristic: • A heuristic *does not guarantee* a solution • It *may contradict* other heuristics • It *reduces* the *search* time in *solving* a problem for a *satisfactory solution* • The *absolute value* of a heuristic…is based on the pragmatic standard…[it] depends exclusively on its *usefulness* in a specific context…a heuristic never dies. It just fades from use. • One heuristic [replaces] another by…*doing a better job* in a given context."
Magee and Frey [39]	"A heuristic is a *generally reliable*, but *potentially fallible*, *simplification* that enables a problem to be addressed within *resource constraints*."
Clancey [40]	"The heuristic classification model characterizes a form of *knowledge* and *reasoning-patterns* of *familiar problem situations* and *solutions*, heuristically related. In capturing problem situations that tend to occur and solutions that tend to work, this *knowledge* is *essentially experiential*, with an overall *form* that is *problem-area independent*."
Maier and Rechtin [41]	"The heuristics methodology is based on "*common sense*,"…comes from *collective experience* stated in as *simple* and *concise* a manner as possible… *Insight*, or the ability to structure a complex situation in a way that greatly increases understanding of it, is strongly guided by *lessons learned* from one's own or others' *experiences* and *observations*. But they *must be used with judgment*." "People typically use heuristics in three ways…[1] as evocative guides. *evoke new thoughts*…[2] as *codifications* of *experience*…[3] as *integrated into development processes*." "Two forms of heuristic[s]…[1] *descriptive*: it *describes* a *situation* but does not indicate directly what to do about it…[2] *prescriptive*: it prescribes *what might be done* about the situation." "Heuristics…are trusted, nonanalytic guidelines for treating *complex*, inherently *unbounded*, ill-structured *problems*….are used as aids in *decision making*, *value judgments*, and *assessments*…provide the successive *transitions* from qualitative, provisional needs to *descriptive* and *prescriptive guidelines* and, hence, to *rational approaches* and *methods*. *Heuristic evaluation criteria* "…to eliminate unsubstantiated assertions," personal opinions, corporate dogma, anecdotal speculation, mutually contradictory statements: • … must *make sense* in its original domain or context…a strong *correlation*, if not a direct *cause and effect*, must be apparent between the heuristic and the successes or failures of specific systems, products, or processes. • The general sense…of the heuristic should *apply beyond the original context*. • The heuristic should be *easily rationalized* in a few minutes or on less than a page. • The *opposite statement* of the heuristic should be *foolish*, clearly not "common sense." • The heuristic's *lesson*, though not necessarily its most recent formulation, should have *stood* the *test* of *time* and earned a broad consensus. • Humor (and *careful choice of words*) in a heuristic provide an emotional bite that enhances the mnemonic effect • For maximum effect, try *embedding both descriptive* and *prescriptive* messages in a heuristic. • *Don't make a heuristic so elegant* that it only has meaning to its creator, thus *losing general usefulness*. • *Rather* than *adding* a *conditional statement* to a heuristic, consider creating a *separate* but *associated heuristic* that focuses on the insight of dealing with that conditional situation."

To synthesize the three previous Secs. 4.1–4.3, the authors pose a set of dimensions that form the definitions of heuristics, guidelines, and principles:

- *Supporting Evidence or Validation Dimension*: the degree of supporting evidence tends to be ordered as heuristics, guidelines, and principles, in increasing evidence.
- *Granularity or Specificity Dimension*: the degree of granularity or specificity tends to be ordered as heuristics, guidelines, and principles, in increasing formalization.
- *Formalization Dimension*: the degree of formalization tends to be ordered as heuristics, guidelines, and principles, in increasing formalization.

- *Prescriptive–Descriptive Dimension*: the nature tends to be ordered as heuristics, guidelines, and principles, progressing from more prescriptive to more descriptive.

4.4 Additional Nomenclature. A number of terms fall into the same family as principles, guidelines, and heuristics, but are not used prevalently in the literature. A few of these terms are reviewed here, as acknowledgment of their importance to, relationship with, or distinction from the three terms defined thus far.

4.4.1 Rule/Commandment. Roozenburg and Eekels discuss design *rules* as dichotomous in nature, either being algorithmic or heuristic. Algorithmic[1] design rules are "based on knowledge where the relationship between cause and effect is known well, as in physical laws, and they produce predictable and reliable results." Heuristic design rules are much less well defined, guaranteed, or proven. They state that "any design rule that cannot be converted into an algorithm is heuristic" [42]. In light of the discussion thus far, were there to be a continuum rather than a dichotomy between algorithmic and heuristic rules, it would be expected that principles might be placed closer to the algorithmic end, heuristics closer to the heuristic end (naturally), with guidelines somewhere in between.

Only one instance of the term *commandment* was encountered in the work of Hamstra [43], which presented a set of seven commandments for exhibit and experience design. The research describes commandments as "not written in stone…[as] creative work cannot be done from a straightjacket of design principles…[they] combine…beliefs about…goals and planning,…methods, and content development. [They]…are designed to spark discussion and inspiration…to clarify ambitions to clients" [43]. Interestingly, the author portrays design principles as restrictive, more so than commandments, despite the semantic connotation of the term. Commandments, as defined, come across as most similar to guidelines, in that they are prescriptive in nature, and based on beliefs rooted in successful design experiences.

4.4.2 Facilitator. Facilitator is a term found in a series of related works that study the design of transformers [10–12]. As stated by the authors, "a Transformation Facilitator is a design archetype that helps or aids in creating mechanical transformation. Transformation Facilitators aid in the design for transformation but their implementation does not create transformation singly" [10–12]. This term harkens to the recommendation of Maier and Rechtin [41]: to create associated heuristics, one is tempted to add a conditional statement—in that there are corollaries and associations among them as well, in addition to being potentially descriptive rather than prescriptive.

4.4.3 State of the Art (SOTA). Koen inextricably links heuristics to the term SOTA [38], which he defines simply as a SOTA, or "a group of heuristics." He goes on to stipulate that "each should be labeled…and…time stamp[ed], [as]…SOTA is a function of time. It changes as new heuristics become useful and are added to it and as old ones become obsolete and are deleted" [38]. As stated earlier in the heuristic section, Koen sees all of engineering as heuristic, so naturally, SOTA practice is defined by those heuristics.

4.4.4 Standard. Standards, as defined by Cheng [44], are "documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines or definitions of characteristics, to ensure that materials, products, process and services are fit for their purpose." This definition has a mix of softer, more subjective words like "agreements" and "guidelines" in combination with more definitive, strong terms like "precise criteria," "technical specifications," and "ensure." One interpretation of these mixed subtexts is that standards are often put into place through governmental regulations, relying upon agreement of law makers and technical experts, and the expertise of the SOTA practices as translated (to the extent possible) into exact numerical specifications. This is no small feat to achieve, let alone articulate.

4.4.5 Algorithm. Suh conceived of Axiomatic Design, from which the definition for *algorithm* and the following definition for *axiom* are taken [45,46]. Suh states, "in purely algorithmic design, we try to identify or prescribe the design process, so in the end the process will lead to a design embodiment that satisfies design goals. Generally, the algorithmic approach is founded on the notion that the best way of advancing the design field is to understand the design process by following the best design practice" [45]. According to Suh, most terms discussed thus far would fit within the category of algorithmic design.

4.4.6 Axiom. Suh goes on to define axioms as "generalizable principles that govern the underlying behavior of the system being investigated. The axiomatic approach is based on the abstraction of good design decisions and processes. As stated earlier, axioms are general principles or self-evident truths that cannot be derived or proven to be true, but for which there are no counterexamples or exceptions. Axioms generate new abstract concepts, such as force, energy and entropy that are results of Newton's laws and thermodynamic laws" [45,46]. While Suh uses the term *principle* in the definition for *axiom*, the requirements for the level of unshakeable truth and correctness of them make axioms the most stringent term discussed yet.

4.4.7 Strategy. Merriam-Webster defines *strategy* as the following:

"1: a careful plan or method for achieving a particular goal usually over a long period of time

2: the skill of making or carrying out plans to achieve a goal" [47]

None of the sources reviewed here directly or explicitly defined *strategy*, but rather used *rule of thumb* as a synonym for other terms, like *principle* or *heuristic*. However, the term *strategy* is particularly relevant to the concept of design principles, as it implies the influence of principle directives/concepts on developing design plans and setting goals. The term *strategy* also provides a scope for design principles regarding their influence on policy, design innovation for organizations, and business.

4.4.8 Rule of Thumb. Merriam-Webster defines *rule of thumb* as the following:

"1: a method of procedure based on experience and common sense

2: a general principle regarded as roughly correct but not intended to be scientifically accurate" [48]

As with strategy, none of the sources reviewed here directly or explicitly defined *rule of thumb*, but rather used *rule of thumb* as a synonym for other terms, like *principle* or *heuristic*.

4.4.9 Analogy and Meta-Analogy. A related or relevant term in a number of the literature sources is *analogy*. Analogies, in this context, are directives that suggest an approach for solutions to design opportunities through the mapping of a source in one domain to a target domain of the opportunity [49,50]. Many design principles in the design research field provide such directives. In fact, many provide categories or domains of analogies at a higher level. We refer to these categories and domains as *meta-analogies*.

5 Design Principles Research Methods

To gauge the SOTA in research methodologies for design principles and their kin, 66 publications were analyzed. From this

[1]An algorithm, as defined by the Oxford Dictionary, is "A process or set of rules to be followed in calculations or other problem-solving operations, especially by a computer." It is important to note that while the word algorithm (and its derivatives) often refers to computational applications, we do not restrict our use to computational applications.

point forward in the paper, the term *principle* is used to refer to itself and any of the other familial terms reviewed in the nomenclature section, as the methods and sources for deriving and validating any of the knowledge codification types reviewed previously is valuable to this analysis. The research efforts analyzed in Sec. 5 include the following Refs. [2,5,8,10–12,14–20,22,24,25,27–29,31,34,37–40,43,51–92]. The topics addressed in the research efforts reviewed include transformational design, biomimetic/bio-inspired design, robotics, software design, user interface design, reconfigurable design, green/environmental design, TRIZ, biomechanical design, and universal design, among others.

In Fig. 4, the proportion of research efforts in the literature that used deductive versus inductive approaches is shown, including those that used both approaches. The majority of researchers used an inductive method, which will be discussed further in Secs. 5.1 and 5.2. The focus of Sec. 5 is to present the methods for derivation and validation of design principles with corresponding sample sizes—to identify trends, gaps, and areas of opportunity. These data and analysis provide a basis for design researchers to understand and choose alternative research methods for future studies, while also having concrete information to judge the veracity of principles presented in published works.

5.1 Review of Methodologies for Extraction/Derivation/Discovery of Design Principles. Each of the 66 references was examined to ascertain the methodology used by the authors to derive, discover, extract, or codify design principles. These were first tabulated as their specific detailed methodologies, and then reduced to broader categories, including:

- *Not Specified or Not Applicable*: the authors did not state the method by which the principles were derived
- *Design Expert Observation*: in situ observation of expert designers at work expressly not a laboratory setting or study
- *Derivation from Laboratory Base Design Practice*: design study-based data was collected, from which principles were extracted
- *Derivation from Design Practice*: based on design performed by the authors, from which principles were derived—can be less time and experience than expert level, otherwise would fall into the next category
- *Experience*: derived from the experience of an expert designer or collection of expert designers, usually the author(s)
- *Existing Principles*: existing literature was used as the source of principles, which were validated or tested using one of the means discussed in Sec. 5.2
- *Analysis of Existing Designs/Design Repositories/Empirical Data Sets*: consumer products, patents, nature, or even software were analyzed

As shown in Fig. 5, most publications derived principles by studying existing designs themselves, a methodology that has the benefit of publicly accessible data sources and large sample sizes. The second most frequent methodology used principles derived by others, a clear deductive approach to design principles research, in which the theory is the starting point of the research confirmed by the validation step. Design experts often write about their career's worth of experiences in a memoir-esque format, sharing their lifelong lessons learned for designers to come. The least prevalent methodologies are those that are highly energy and resource intensive in terms of observation, data collection, data coding, and analysis. Only a few papers failed to specify where the principles came from or how they were derived.

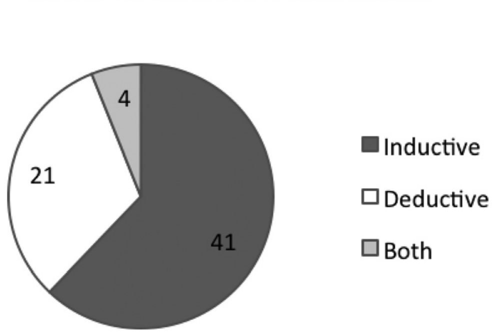

Fig. 4 Research method classification for analyzed literature

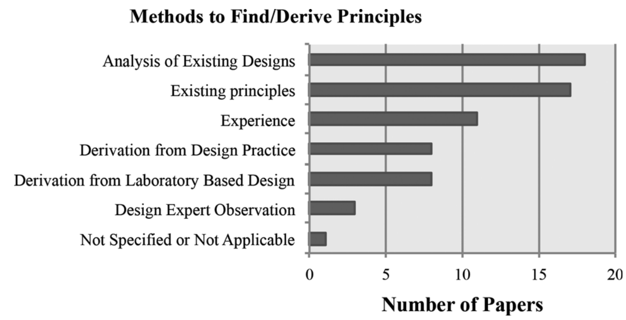

Fig. 5 Methods used in literature to derive design principles

Figure 6 shows the sources that researchers used to derive principles. Many cited multiple sources, using, for example, both consumer products and literature review. If the authors generated principles from their own design activities, it was coded as "authors," rather than "design project/task." This choice was made to illustrate that many authors and researchers are writing about their own design experiences, lessons, and accumulated knowledge, rather than deriving it from an external source. The categories shown in Fig. 6 are described as the following:

- *Design Project/task*: designers/study subjects performed a design task
- *Students*: students served as the subjects for a design study
- *Not Specified/Not Applicable*: the authors did not state the source
- *Expert Designers from Industry*: expert industrial designers were observed, interviewed, or studied as the source
- *Nature*: natural phenomena, as in biologically inspired or biomimetic design
- *Designers*: designers performed design tasks, neither novices nor experts, nor architects, engineers or roboticists—a middle category for design study subjects
- *Authors*: the authors of the research publication served as the source either through design activity or experiential knowledge
- *Patents*: patents were analyzed as the source

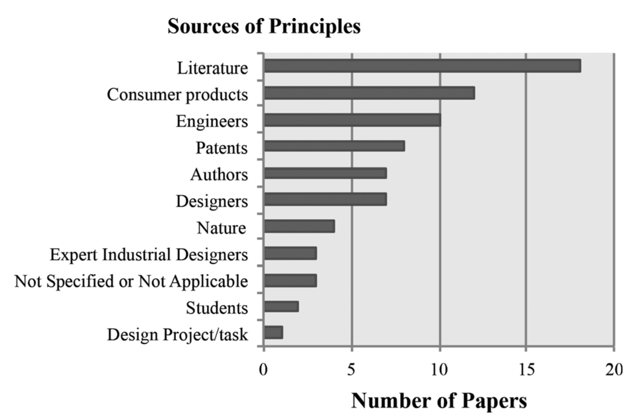

Fig. 6 Sources from which design principles were extracted

Table 4 Sample sizes used in literature to derive principles

Methods to find principles	Unit of sample size	Sample size
Analysis of existing designs	Consumer products	10, 46, 23, 15, 10, 3
	Consumer products, patents	190, 90
	Consumer products, patents, nature	190, N/A
	Examples	163
	Nature	1
	Patents	200,000, 41
	Computer programs	N/A
	Reconfigurable systems	33
Analysis of existing designs, existing principles	Patents	90
Derivation from design practice	Design project/task	2, 1, 1
	Engineers	N/A
	N/A (3)	N/A (3)
Derivation from laboratory based design practice	Design project/task	5
	Designers	N/A (2), 20
	Engineers	36
	Students	300, 29
	Teams	12
Design expert observation	Designs (sketches, early stage)	50
	(Person) years	0.5
	N/A	N/A
Existing principles	Literature	N/A (5), 442, 10, 3, 2
	N/A (6)	N/A (6)
Existing principles, experience	N/A (2)	N/A (2)
Experience	N/A (2)	N/A (2)
	(Person) years	30, 40, 40, 40, 40, 20, 1, N/A (2)

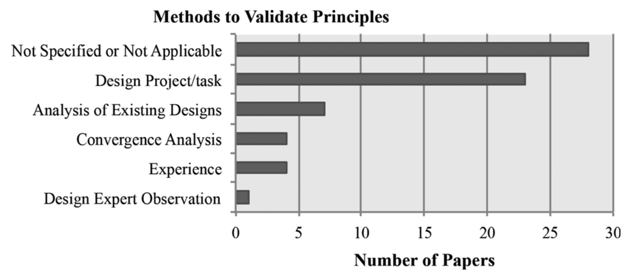

Fig. 7 Methods used in literature to validate design principles

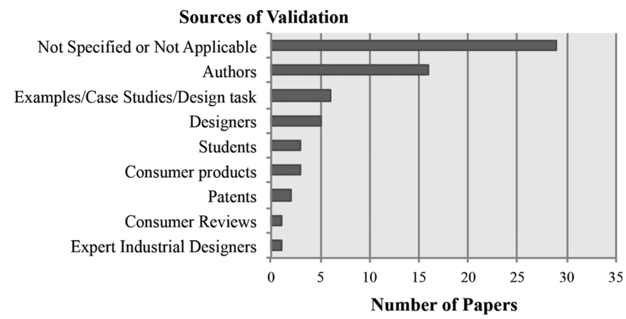

Fig. 8 Sources used in literature to validate design principles

- *Engineers*: engineers were studied, observed, or interviewed as the source
- *Consumer products*: consumer products were analyzed to extract principles
- *Literature*: principles were taken as already articulated in pre-existing literature

The sample sizes used for the derivation of the principles were also tabulated, as shown in Table 4. If any information was not included, "N/A" was marked. Numbers in parentheses denote the number of papers that did not specify that particular information. The largest sample sizes came from analysis based on student participant design studies, patent/consumer product analyses, and individuals reporting on their own person-years of experience.

5.2 Review of Methodologies for Validation of Design Principles. Similar to the analysis in Sec. 5.1, the source literature was also examined for the ways in which they validated the design principles that were derived. Figure 7 shows that the majority of publications did not address the validation of the principles, but rather focused on the derivation of the principles, or more often, the pure presentation of the principles themselves, without regard for methodology. The second most prevalent validation methodology was a design project or task—most often a case study of solving 1–3 design problems employing the design principles. The results shown in Figs. 7 and 8 indicate a need for greater validation effort within design principle research. Interestingly, a niche in the publication set [12,79,85] is represented by those who validated principles through:

Convergence/Asymptotic Analysis: *Examining a larger set of source material (test data) until the quantity of principles converged to a horizontal asymptote, i.e., asymptotic convergence. This numerical technique shows promise for its computational robustness, but does not address the validation of the utility of the principles.*

As expected, based on the number of publications that did not address validation methodology, the source for validation was not addressed for the majority of publications (Fig. 8). Most often, the authors or others performed small-scale implementations of the design principles in practice, as proof of concept and initial validation at a case study level.

Sample sizes used for principle validation were also tabulated, as they were for derivation. Table 5 shows the samples sizes and units of those samples for each paper analyzed. Nearly half (28) of the papers did not report the method to validate principles, the source, nor the sample size. The largest sample sizes came from consumer products analyses, patent analyses, and customer review analyses. Most papers went about validation with 1–3 design tasks implementing the derived principles.

6 Semantic Principle Analysis

A total of 858 principles/heuristics/guidelines were collected from the literature review in order to perform a computational semantic analysis. The goal was to determine if there were

Table 5 Sample Sizes Used in Literature for Principle Validation

Methods to validate principles	Unit of sample size	Sample size
Analysis of existing designs	Consumer products	4, 17, 70, 645
	Industrial products	2
	N/A (2)	N/A (2)
Convergence analysis	Customer reviews	200
	Patents	41, 50
Convergence analysis, design project/task	Design project/task	1
Design expert observation	Designs	218
Design project/task	Design project/task	1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 2, 2, 3, 3, 3, 4, 4, 28
	Students	6, 64, N/A
	Team	1
Experience	N/A (4)	N/A (4)
N/A (28)	N/A (28)	N/A (28)

patterns in the way principles have been articulated thus far, mainly focusing on the parts of speech and order of those parts of speech. With an understanding of the semantic patterns of principle articulation, we can make recommendations about how they should be formally expressed in future work.

Our hypothesis was that there would be two main patterns that emerge in the linguistic structures of the principles:

(1) Most principles will be stated in the linguistic imperative form, indicating a prescriptive instruction for how to go about doing design successfully.
(2) Some principles will be stated in the linguistic declarative form, indicating a descriptive statement about the nature of a particular design space or application.

Imperative sentences are commands, an order, or a firm request. Imperative sentences can be detected computationally by finding the presence of the command conjugation of an action verb, which is most often at or very near the beginning of the sentence [93]. For example, "Keep it simple," a classic adage and design principle, is an imperative sentence, where the word *keep* is the imperative form of the infinitive verb *to keep*.

Declarative sentences are more difficult to detect computationally, as the majority of sentences are declarative. Declarative sentences make a statement or assertion. Declarative sentences consist of two main components: (1) a subject, which is a noun phrase or nominative personal pronoun, and (2) a predicate, which completes an idea about the subject, such as what it does or what it is like. A predicate consists of a finite (as opposed to infinitive) verb and all of the words modifying it [93]. For example, "All engineering is heuristic," as *declared* by Koen [38], consists of the subject—*All engineering*—and the predicate—*is heuristic*.

Each principle, in its entirety, whether single or multiple sentences, was computationally analyzed to extract the part of speech of each word in order. Design principles were collected from the papers in the literature review. Each principle was placed in a separate row of a matrix, with some comprising of only one word, some one sentence, some an entire paragraph. Each principle (row of the matrix) was then processed using TreeTagger [94,95] to extract the part of speech types and orders. Here, we focus on different conjugations of verb types, nouns, adverbs, and adjectives. All other parts of speech have been omitted from the analysis for brevity (for example, articles like "a" and "the"). TreeTagger separately tags three particular verbs that are very common—"to be," "to do," and "to have." In Fig. 9, analyses including and excluding these particular verbs are plotted. The logic of examining an analysis excluding these particular verbs is that, given their extreme commonness in the English language, omitting them may yield less noisy results. One can see that the overall quantity of verbs declines slightly in some conjugations, and more drastically in others, when *be*, *do,* and *have* are omitted. However, the overall trends remain the same. The verb base form, also called the infinitive, root, or imperative form, dominates the part of speech type counts within the principles, showing initial support for Hypothesis 1. After other verb forms, nouns account for second most common part of speech type in this analysis, potentially supporting Hypothesis 2.

Figure 10 shows the patterns that emerged from a second analysis. The plot shows word and sentence order along the horizontal axis. Along the vertical axis is the number of principles containing that particular part of speech at the particular word position (i.e., first word, second word, etc.) within the first five sentences.

The analysis in Fig. 10 indicates very strong support for Hypothesis 1, showing that most principles in this sample set begin with an imperative verb. This result most likely indicates the presence of a prescriptive instruction for how to go about doing design successfully. Nouns are significantly less represented in the first five sentences of each design principle, again indicating that most principles are expressed in the linguistic imperative form, rather than the linguistic declarative form. From this analysis, we conclude that research practice accepts the form of the linguistic imperative more commonly for the formal articulation of design principles, though not exclusively.

While insightful, these results are not entirely unexpected. From a recent book on the topic, there is affirmation of the importance of verbs in linguistics and conceptual representation. The authors state, "Verbs play an important role in how events, states and other "happenings" are mentally represented and how they are expressed in natural language. Besides their central role in linguistics, verbs have long been prominent topics of research in analytic philosophy—mostly on the nature of events and predicate-argument structure—and a topic of empirical investigation in psycholinguistics, mostly on argument structure and its role in sentence comprehension. More recently, the representation of verb meaning has been gaining momentum as a topic of research in other cognitive science branches, notably neuroscience and the psychology of concepts" [96]. Work in engineering design and biomimicry by Chiu and Shu [97] emphasizes and examines the usefulness of verbs in expressing functionality in design, as formerly established by the functional basis [98].

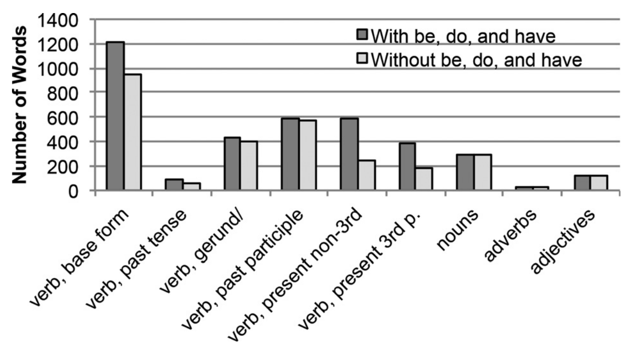

Fig. 9 Part of speech word position semantic principle analysis

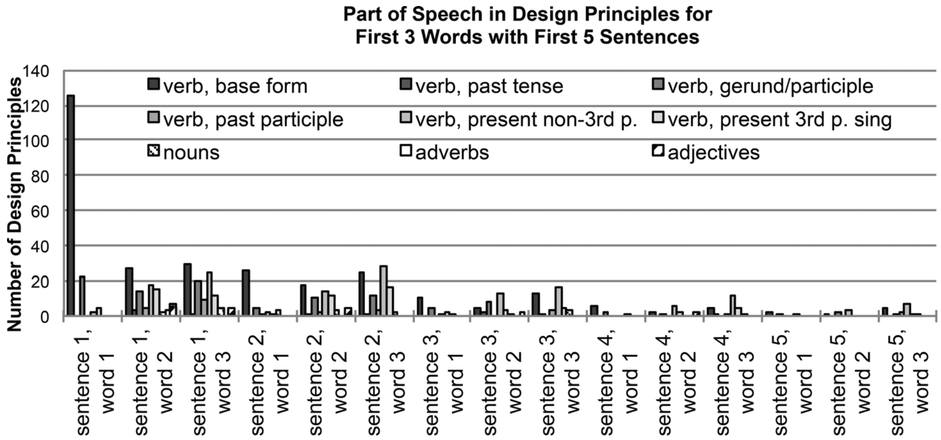

Fig. 10 Quantities by part of speech of first three words in first five sentences for set of design principles

7 Proposed Formalization of Principle Articulation

Based on the analysis presented in Sec. 6, we propose an empirically based grammatical formulation for the articulation of design principles, validating and building upon that proposed by Greer et al. [22], which is prior work on which co-author Wood was a collaborator. Greer et al. states: "The format used to present the…design [principles] is the *imperative form* from English grammar. The imperative form is used to construct verb phrases that make requests, give directions or instructions, or give orders or commands, where the context here is to give directions or instructions. This format is consistent with the *action-centered guideline model* used by Nowack [23], where a design cycle operates from an initial *issue*, which motivates an *action* that produces a *consequence*, which in turn must be evaluated to see if it satisfies the original *issue*. In the model, [design principles] embody the action that taken to address *issue*. The result of the [design principle] application, or *action*, is the *consequence*" [22].

Drawing from the analysis in Sec. 6, we assert that design principles should, for the most part, be articulated in the imperative form and not declarative form. There should be a prescriptive *action* described in the design principle, not just a description of the nature of a subject. Design being an active process, we argue that design principles should be imperative and action centered, as Nowack does [23].

Therefore, we propose the following formal requirements for the articulation of *prescriptive* design principles:

A Prescriptive Design Principle:

- Is stated in the grammatical imperative form.
- Includes a prescriptive action for a designer to take
- Increases the likelihood of reaching a desirable consequence, which must also be explicitly articulated
- Is situated within a particular context and point in time, so as to provide information regarding the scope of the area of application/relevance and current state of the art in the field

Example Prescriptive Design Principle. "In the context of design for flexibility, reduce the effect of a change in a design by increasing the number of partitions. This will lessen the impact of any individual element on the whole if a change becomes necessary for the element in question." [76]

Alternatively, design principles can describe the current state of the field, SOTA, or foundational theory behind an area of application. These types of design principles take on the linguistic declarative form, and serve as informative statements, rather than prescriptive directions.

Therefore, we propose the following formal requirements for the articulation of *descriptive* design principles:

A Descriptive Design Principle:

- Is stated in the grammatical declarative form.
- Informs the designer/reader of some fundamental concept, fact, or acquired knowledge about a particular field of application
- Is situated within a particular context and point in time, so as to provide information regarding the scope of the area of application/relevance and current state of the art in the field

Example Descriptive Design Principle. "Testing the product in the actual setting is an essential part of design for the developing world, not merely a final step. Importing technology without adapting it to the specific developing world context is ineffective and unsustainable." [16]

8 Proposed Future Directions for Design Principles Research Methodology

The review of the design principles literature indicates some key opportunities for future directions of DRM. First, most research efforts focus on the presentation of principles themselves, with very few offering any prescriptive application of these principles into design practice for their validation. Author experience should be combined with empirical derivation/discovery of design principles, so as to combine the benefits of longitudinal expertise and reduction of bias in reporting on just one personal perspective/experience. As is true of much of design science research, more investment must be made into the study of expert designers, regardless of energy/time/resource intensive requirements—or alternatively, a solution to this problem should be developed. As an example, this issue of sample size and access to expert/advanced level design participants is being addressed innovatively through efforts like the use of crowd-sourced design and other online platforms [99].

There is also an opportunity for more computational and numerical validation of the principles, through techniques like convergence analysis referenced earlier [12,79,85]. Alternative computational validation might include other data mining techniques, agent-based modeling of design processes, modeling of human cognition through Bayesian statistics or other philosophical approaches, artificial intelligence models implementing methods like neural networks, decision trees, and complex systems modeling. An increased level of formalism in the articulation of principles, using tools like logic operators, language structures, etc., is an additional way to add rigor and repeatability to the research methodology.

As discussed above, there are dimensions of principles that emerge from the various definitions that should be considered, or even explicitly stated, including level of supporting evidence or validation, level of granularity or specificity, level of formalization, and position on the spectrum of prescriptive–descriptive. Other important aspects to consider when articulating design principles are the time stamp (to indicate a sense of where state of the art, technological, social, and economic trends stand in relation to the principle), the context in which the principle is usable/useful/relevant, the intended users of the principle, any expected background/knowledge for proper application, and any conditions or qualifiers for applicability. Design principles should also be readable by humans and understandable by designers. Given the common reference to increasing the designer's chances for success, it would be highly valuable to include a metric or dimension of *likelihood of success* in using the principle. However, this would require specific investigation beyond the scope of the literature in extraction of data, such as experiments with each of the principles tested with different designer types, problems, and contexts. With this type of inquiry, *likelihood of success* could be rigorously qualified or quantified.

9 Conclusions

Design Science, or in general design research, has received increasing attention over the last few decades. The future of products, services, systems, software, and architecture relies on advancing design, both in terms of our foundation/formalized understanding and our inspirations for practitioners. Design principles represent a key component of description and characterization of design and associated design processes.

In this paper, we study past contributions to the area of design principles, developing a discourse for, definitions of, and distinctions among related formalizations. Key contributions of this work include working definitions for researchers and practitioners to investigate, share, and utilize. These definitions may be used not only to share and describe design principles across design communities, but also as part of disciplinary fields. We analyze different research methodologies, highlighting derivation, validation, and sample size in past design principles research. Researchers from disparate fields may engage the explored methodologies to improve the rigor of their studies, as well as consider the recommendations for even greater rigor for the research field. Future directions include further formalization of methodologies for design principles research, and implementation/validation of those methodologies with applications in the areas of digital design for manufacturing and bio-inspired design.

We hope that this work will make an impact in a number of ways. This work will be valuable to researchers who are newly entering the field. The synthesis of the research in this area will be helpful for getting up to speed quickly, identifying new directions and areas for improvement for future work. For those who are already experienced in this research area, the paper presents a valuable new approach to consider. This paper provides formalization to an area in which researchers have been publishing for nearly 70 years, bringing structure and synthesis to a complex and multidisciplinary body of literature, molding it into a form that can now be wielded by future researchers much more aptly. The work also creates an opportunity for talented domain researchers to step into the realm of formulating design principles in their specific application areas, which is crucial to the maturation of design practice within those fields.

We recognize and acknowledge that design is prescientific, as a field of research. In our view, design science will take a form closer to behavioral economics because there will generally be a human element to design. This human element adds a level of complexity, unpredictability, and heterogeneity that comes from the diverse nature of people themselves. It is difficult to imagine how we can control or account for all elements that make human beings (and thus designers) so beautifully diverse and complex. At the same time, there is scholarship and value in categorizing, synthesizing, and presenting the current SOTA within design research. The aim is to help others learn about design, design principles, and current best practices. The literature review and analysis in this paper is a snapshot of the present, based on previous knowledge that will change as new knowledge is gained.

Acknowledgment

This work was funded by the SUTD-MIT International Design Centre (IDC)[2].

References

[1] Papalambros, P. Y., 2015, "Design Science: Why, What and How," Des. Sci., **1**, p. e1.
[2] Glegg, G. L., 1969, *The Design of Design*, Cambridge University Press, Cambridge, UK.
[3] Fu, K., Yang, M. C., and Wood, K. L., 2015, "Design Principles: The Foundation of Design," ASME Paper No. DETC2015-46157.
[4] Pahl, G., and Beitz, W., 1988, *Engineering Design: A Systematic Approach*, Springer-Verlag, London.
[5] Blessing, L. T. M., and Chakrabarti, A., 2009, *DRM, A Design Research Methodology*, Springer, Dordrecht, The Netherlands.
[6] Finger, S., and Dixon, J. R., 1989, "A Review of Research in Mechanical Engineering Design—Part II: Representations, Analysis, and Design for the Life Cycle," Res. Eng. Des., **1**(2), pp. 121–137.
[7] Finger, S., and Dixon, J. R., 1989, "A Review of Research in Mechanical Engineering Design—Part I: Descriptive, Prescriptive, and Computer-Based Models of Design Processes," Res. Eng. Des., **1**(1), pp. 51–67.
[8] Gruber, T. R., 1995, "Toward Principles for the Design of Ontologies Used for Knowledge Sharing," Int. J. Hum.-Comput. Stud., **43**(5–6), pp. 907–928.
[9] Merriam-Webster, 2016, Definition of Principle, http://www.merriam-webster.com/dictionary/principle, Encyclopædia Britannica, Inc., Chicago, IL.
[10] Moe, R. E., Jensen, D., and Wood, K. L., 2004, "Prototype Partitioning Based on Requirement Flexibility," ASME Paper No. DETC2004-57221.
[11] Weaver, J. M., Wood, K. L., and Jensen, D., 2008, "Transformation Facilitators: A Quantitative Analysis of Reconfigurable Products and Their Characteristics," ASME Paper No. DETC2008-49891.
[12] Singh, V., Skiles, S. M., Krager, J. E., Wood, K. L., Jensen, D., and Sierakowski, R., 2009, "Innovations in Design Through Transformation: A Fundamental Study of Transformation Principles," ASME J. Mech. Des., **131**(8), p. 081010.
[13] Bell, P., Hoadley, C. M., and Linn, M. C., 2004, "Design-Based Research in Education," *Internet Environments for Science Education*, M. C. Linn, E. A. Davis, and P. Bell, eds., Lawrence Erlbaum Associates, Mahwah, NJ, pp. 73–85.
[14] Kali, Y., 2008, "The Design Principles Database as Means for Promoting Design-Based Research," *Handbook of Design Research Methods in Education: Innovations in Science, Technology, Engineering: Mathematics Learning and Teaching*, A. E. Kelly, R. A. Lesh, and J. Y. Baek, eds., Routledge, New York, pp. 423–438.
[15] Anastas, P. T., and Zimmerman, J. B., 2003, "Design Through the 12 Principles of Green Engineering," Environ. Sci. Technol., **37**(5), pp. 94A–101A.
[16] Mattson, C. A., and Wood, A. E., 2014, "Nine Principles for Design for the Developing World as Derived From the Engineering Literature," ASME J. Mech. Des., **136**(12), p. 121403.
[17] McAdams, D. A., 2003, "Identification and Codification of Principles for Functional Tolerance Design," J. Eng. Des., **14**(3), pp. 355–375.
[18] Perez, A., Linsey, J., Tsenn, J., and Glier, M., 2011, "Identifying Product Scaling Principles: A Step Towards Enhancing Biomimetic Design," ASME Paper No. IMECE2011-63975.
[19] Sobek, D. K., II, Ward, A. C., and Liker, J. K., 1999, "Toyota's Principles of Set-Based Concurrent Engineering," Sloan Management Review, Winter 1999, Vol. 40.
[20] Altshuller, H., 1994, *The Art of Inventing (And Suddenly the Inventor Appeared)*, Technical Innovation Center, Worcester, MA.
[21] Merriam-Webster, 2016, *Definition of Guideline*, http://www.merriam-webster.com/dictionary/guideline, Encyclopædia Britannica, Inc., Chicago, IL.
[22] Greer, J. L., Greer, J. L., Wood, J. J., Jensen D. D., and Wood, K. L., 2002, "Guidelines for Product Evolution Using Effort Flow Analysis: Results of an Empirical Study," ASME Paper No. DETC2002/DTM-34013.
[23] Nowack, M. L., 1997, "Design Guideline Support for Manufacturability," Ph.D. thesis, Engineering Department, Cambridge University, Cambridge, UK.
[24] Kim, H., 2010, "Effective Organization of Design Guidelines Reflecting Designer's Design Strategies," Int. J. Ind. Ergon., **40**(6), pp. 669–688.
[25] Nielsen, J., 1993, *Usability Engineering*, Academic Press, Boston, MA.
[26] Bevan, N., and Spinhof, L., 2007, "Are Guidelines and Standards for Web Usability Comprehensive?," *Human-Computer Interaction. Interaction Design and Usability*, J. A. Jacko, ed., Springer, Heidelberg, Germany, pp. 407–419.
[27] Jaünsch, J., and Birkhofer, H., 2006, "The Development of the Guideline VDI 2221—The Change of Direction," International Design Conference, Dubrovnik, Croatia, pp. 45–52.

[2]http://idc.sutd.edu.sg

[28] Matthews, P. C., 1998, "Using a Guideline Database to Support Design Emergence: A Proposed System Based on a Designer's Workbench," 5th International Conference on Artificial Intelligence in Design, AID98, Workshop: Emergence in Design, S. Chase and L. Schmidts, eds., Lisbon, Portugal, pp. 13–18.

[29] Telenko, C., and Seepersad, C., 2010, "A Methodology for Identifying Environmentally Conscious Guidelines for Product Design," ASME J. Mech. Des., **132**(9), p. 091009.

[30] Merriam-Webster, 2016, *Definition of Heuristic*, http://www.merriam-webster.com/dictionary/heuristic, Encyclopædia Britannica, Inc., Chicago, IL.

[31] Stone, R., and Wood, K. L., 2000, "A Heuristic Method for Identifying Modules for Product Architectures," Des. Stud., **21**(1), pp. 5–31.

[32] Bolc, L., and Cytowshi, J., 1992, *Search Methods for Artificial Intelligence*, Academic Press, London.

[33] Li, C. L., Tan, S. T., and Chan, K. W., 1996, "A Qualitative and Heuristic Approach to the Conceptual Design of Mechanism," Eng. Appl. Artif. Intell., **9**(1), pp. 17–32.

[34] Chong, Y. T., Chen, C.-H., and Leong, K. F., 2009, "A Heuristic-Based Approach to Conceptual Design," Res. Eng. Des., **20**(2), pp. 97–116.

[35] Nisbett, R. E., and Ross, L., 1980, *Human Inference: Strategies, and Shortcomings of Social Judgment*, Prentice-Hall, Englewood Cliffs, NJ.

[36] Pearl, J., 1984, *Heuristics: Intelligent Search Strategies for Computer Problem Solving*, Addison-Wesley Publishing Co., Reading, MA.

[37] Yilmaz, S., and Seifert, C., 2011, "Creativity Through Design Heuristics: A Case Study of Expert Product Design," Des. Stud., **32**(4), pp. 384–415.

[38] Koen, B. V., 1985, *Definition of the Engineering Method*, ASEE Publications, Washington, DC.

[39] Magee, C., and Frey, D., 2006, "Experimentation and Its Role in Engineering Design: Linking a Student Design Exercise to New Results From Cognitive Psychology," Int. J. Eng. Educ., **22**(3), pp. 478–488.

[40] Clancey, W. J., 1985, "Heuristic Classification," Artif. Intell., **27**(3), pp. 289–350.

[41] Maier, M. W., and Rechtin, E., 2000, *The Art of Systems Architecting*, Vol. 2, CRC Press, Boca Raton, FL.

[42] Roozenburg, N. F. M., and Eekels, J., 1995, *Product Design: Fundamentals and Methods*, Wiley, Chichester, UK.

[43] Hamstra, E., 2012, "Seven Commandments of an Experience Design Company," Dimensions, ASTC, Washington, DC, pp. 36–39.

[44] Cheng, M., 2003, *Medical Device Regulations: Global Overview and Guiding Principles*, World Heath Organization, Geneva, Switzerland.

[45] Suh, N. P., 2001, *Axiomatic Design: Advances and Applications*, Oxford University Press, New York.

[46] Suh, N. P., 1990, *The Principles of Design*, Oxford University Press, New York.

[47] Merriam-Webster, 2016, *Definition of Strategy*, http://www.merriam-webster.com/dictionary/strategy, Encyclopædia Britannica, Inc., Chicago, IL.

[48] Merriam-Webster, 2016, *Definition of Rule of Thumb*, http://www.merriam-webster.com/dictionary/rule%20of%20thumb, Encyclopædia Britannica, Inc., Chicago, IL.

[49] Hey, J., Linsey, J., Agogino, A., and Wood, K. L., 2008, "Analogies and Metaphors in Creative Design," Int. J. Eng. Educ., **24**(2), pp. 283–294.

[50] Markman, A. B., and Wood, K. L., 2009, *Tools for Innovation: The Science Behind Practical Methods That Drive New Ideas*, Oxford University Press, New York.

[51] Altshuller, G. S., 1984, *Creativity as an Exact Science—The Theory of the Solution of Inventive Problems* (Studies in Cybernetics), Gordon and Breach Publishers, Amsterdam, The Netherlands.

[52] Ammar, A. A., Scaravetti, D., and Nadeau, J.-P., 2010, "A Heuristic Method for Functional Aggregation Within the Design Process," IDMME-Virtual Concept, Bordeaux, France, Oct. 20–22.

[53] Armstrong, J., 2004, "Design Principles: The Engineer's Contribution to Society," Royal Academy of Engineering, London.

[54] Bardram, J. E., 2004, "Applications of Context-Aware Computing in Hospital Work: Examples and Design Principles," CM Symposium on Applied Computing, Nicosia, Cyprus, March 14–17.

[55] Campbell, R. D., Lewis, P. K., and Mattson, C. A., 2011, "A Method for Identifying Design Principles for the Developing Worlds," ASME Paper No. DETC2011-48584.

[56] Cormier, P., Literman, B., and Lewis, K., 2011, "Empirically Derived Heuristics to Assist Designers With Satisfying Consumer Variation in Product Design," ASME Paper No. DETC2011-48448.

[57] Daly, S., Yilmaz, S., Christian, J. L., Seifert, C. M., and Gonzalez R., 2012, "Design Heuristics in Engineering Concept Generation," J. Eng. Educ., **101**(4), pp. 601–629.

[58] Yilmaz, S., Daly, S., Seifert, C.M., and Gonzalez, R., 2010, "Cognitive Heuristic Use in Engineering Design Ideation," ASEE Annual Conference, Louisville, KY, June 20–23, pp. 15.282.1–15.282.25.

[59] Dismukes, J. P., 2005, "Information Accelerated Radical Innovation From Principles to an Operational Methodology," The Industrial Geographer, Vol. 3, pp. 19–42.

[60] Dong, A., and Agogino, A. M., 2001, "Design Principles for the Information Architecture of a SMET Education Digital Library," JCDL, Roanoke, VA.

[61] Esposito, N., and Linsey, J. L., 2012, "Principles of Green Design: Analyzing User Activities and Product Feedback," ASME Paper No. DETC2012-71197.

[62] Galle, P., 1996, "Design Rationalization and the Logic of Design: A Case Study," Des. Stud., **17**(3), pp. 253–275.

[63] Glegg, G. L., 1972, *The Selection of Design*, Vol. 74, Cambridge University Press, Cambridge, UK.

[64] Glegg, G. L., 1973, *The Science of Design*, Cambridge University Press, Cambridge, UK.

[65] Glegg, G. L., 1981, *The Development of Design*, Cambridge University Press, Cambridge, UK.

[66] Gunther, J., and Ehrlenspiel, K., 1999, "Comparing Designers From Practice and Designers With Systematic Design Education," Des. Stud., **20**(5), pp. 439–451.

[67] Houssin, R., and Coulibaly, A., 2011, "An Approach to Solve Contradiction Problems for Safety Integration in Innovative Design Process," Comput. Ind., **62**(4), pp. 398–406.

[68] Joseph, S., 1996, "Design Systems and Paradigms," Des. Stud., **17**(3), pp. 227–239.

[69] Keese, D. A., Tilstra, A. H., Seepersad, C. C., and Wood, K. L., 2007, "Empirically-Derived Principles for Designing Products With Flexibility for Future Evolution," ASME Paper No. DETC2007-35695.

[70] Langheinrich, M., 2001, "Privacy by Design—Principles of Privacy-Aware Ubiquitous Systems," Ubicomp 2001: Ubiquitous Computing International Conference, Atlanta, GA, Sept. 30–Oct. 2, Springer-Verlag, Berlin, pp. 273–291.

[71] Liker, J. K., 2004, *The Toyota Way—14 Management Principles From the World's Greatest Manufacturer*, McGraw-Hill, New York.

[72] Matthews, P. C., Blessing, L. T. M., and Wallace, K. M., 2002, "The Introduction of a Design Heuristics Extraction Method," Adv. Eng. Inf., **16**(1), pp. 3–19.

[73] Mulet, E., and Vidal, R., 2008, "Heuristic Guidelines to Support Conceptual Design," Res. Eng. Des., **19**, pp. 101–112.

[74] Norman, D., 1988, *The Design of Everyday Things*, Basic Books, New York.

[75] Rajan, P. K. P., Van Wie, M., Campbell, M., Otto, K., and Wood. K., 2003, "Design for Flexibility—Measure and Guidelines," ICED, Stockholm, Sweden.

[76] Rajan, P. K. P., Van Wie, M., Campbell, M. I., Wood, K. L., and Otto, K. N., 2005, "An Empirical Foundation for Product Flexibility," Des. Stud., **26**(4), pp. 405–438.

[77] Pfeifer, R., Iida, F., and Bongard, J., 2005, "New Robotics: Design Principles for Intelligent Systems," Artif. Life, **11**(1–2), pp. 99–120.

[78] Poole, S., and Simon, M., 1997, "Technological Trends, Product Design and the Environment," Des. Stud., **18**(3), pp. 237–248.

[79] Qureshi, A., Murphy, J. T., Kuchinsky, B.,Seepersad, C. C., Wood, K.L., and Jensen, D.D., 2006, "Principles of Product Flexibility," ASME Paper No. DETC2006-99583.

[80] Raviv, D., 2004, "Hands-On Inventive Solutions in Engineering Design," ASEE Annual Conference and Exposition, Salt Lake City, UT, Paper No. 2001089.

[81] Reichert, S. H., 2010, "Reverse Engineering Nature: Design Principles for Flexible Protection. Inspired by Ancient Fish Armor of Polypteridae," S.M. thesis, Department of Architecture, Massachusetts Institute of Technology, Cambridge, MA.

[82] Resnick, M., Myers, B., Nakakoji, K., Shneiderman, B., Pausch, R., Selker, T., and Eisenberg, M., 2005, "Design Principles for Tools to Support Creative Thinking," Institute for Software Research, Paper No. 816.

[83] Sangelkar, S., Cowen, N., and McAdams, D., 2012, "User Activity—Product Function Association Based Design Rules for Universal Products," Des. Stud., **33**(1), pp. 85–110.

[84] Siddiqi, A., and de Weck, O. L., 2008, "Modeling Methods and Conceptual Design Principles for Reconfigurable Systems," ASME J. Mech. Des., **130**(10), p. 101102.

[85] Singh, V., Skiles, S. M., Krager, J. E., Wood, K. L., Jensen, D., Szmerekovsky, A., 2006, "Innovations in Design Through Transformation: A Fundamental Study of Transformation Principles," ASME Paper No. DETC2006-99575.

[86] Son, J. I., Raulf, C., Cheong, H., and Shu, L. H., 2012, "Applying Patterns of Transformation in Biology to Design," ASME Paper No. DETC2012-71296.

[87] Sosa, R., Wood, K. L., and Mohan, R. E., 2014, "Identifying Opportunities for the Design of Innovative Reconfigurable Robots," ASME Paper No. DETC2014-35568.

[88] Tilstra, A. H., Backlund, P. B., Seepersad, C.C., and Wood, K.L., 2008, "Industrial Case Studies in Product Flexibility for Future Evolution: An Application and Evaluation of Design Guidelines," ASME Paper No. DETC2008-49370.

[89] Wallace, K. M., 1995, "Methods and Tools for Decision Making in Engineering Design," Des. Stud., **16**(4), pp. 429–446.

[90] Weaver, J., Wood, K. L., Crawford, R., and Jensen, D., 2010, "Transformation Design Theory: A Meta-Analogical Framework," ASME J. Comput. Inf. Sci. Eng., **10**(3), p. 031012.

[91] Yammiyavar, P., 2005, "Usability Heuristics and Their Role in Designing Vehicles—A Case Study of an Electric-Hybrid Vehicle Body Design," J. Indian Inst. Sci., **85**(2), pp. 67–82.

[92] Zanakis, S. H., Evans, J. R., and Vazacopoulos, A. A., 1989, "Heuristic Methods and Applications: A Categorized Survey," Eur. J. Oper. Res., **43**(1), pp. 88–110.

[93] Garner, B. A., 2009, *Garner's Modern American Usage*, 3rd ed., Oxford University Press, New York.

[94] Schmid, H., 1999, "Improvements in Part-of-Speech Tagging With an Application to German," Text, Speech and Language Tech., 11, pp. 13–25.

[95] Schmid, H., 1994, "Probabilistic Part-of-Speech Tagging Using Decision Trees," International Conference on New Methods in Language Processing, Manchester, UK.

[96] R. G. de Almeida, and C. Manouilidou, Eds., 2014, *Cognitive Science Perspectives on Verb Representation and Processing*, Springer, Heidelberg, Germany.
[97] Chiu, I., and Shu, L. H., 2007, "Biomimetic Design Through Natural Language Analysis to Facilitate Cross-Domain Information Retrieval," Artif. Intell. Eng. Des., Anal. Manuf., AIEDAM, **21**(1), pp. 45–59.
[98] Stone, R., and Wood, K. L., 2000, "Development of a Functional Basis for Design," ASME J. Mech. Des., **122**(4), pp. 359–370.
[99] Chan, J., Dow, S. P., and Schunn, C. D., 2015, "Do the Best Design Ideas (Really) Come From Conceptually Distant Sources of Inspiration?," Des. Stud., **36**, pp. 31–58.