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Affordance based design: a relational theory for design

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Abstract After reviewing current approaches to design theory, which are based on the transformative concept of function, we argue that this basis in function limits the scope of design problems and explanatory power of current design theories. As an alternative with greater potential for explanatory power and a framework for solving a wider array of design problems, we propose that a relational theory of design is needed. Such a relational theory should mirror those currently developed in mathematics, physics, computer science, and even philosophy. We develop a relational theory for design based on the concept of affordances from perceptual psychology. Affordances help to explain the entanglement between designers, users, and artifacts—relationships that are not currently handled by function based approaches to design. Affordance based design, as developed in this paper, does not offer a radical new approach to doing design, but rather a shift in design thinking. Our focus in this paper is therefore on the explanatory power and potential innovation fostered by this change in design thinking, as illustrated through several examples, and not on specific methods.

Keywords Affordances · Affordance based design · Design theory

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1 Introduction: the opportunity for a new design theory

Since its inception some 50 years ago, the field of design theory and methodology has produced much useful research to aid engineers in designing both classical machines and more modern artifacts. However, current approaches encounter difficulty with the design of some fairly common, and even simple devices. Take for example, the design of an electrical motor. The function of the motor is fairly straight-forward. It transforms electrical energy into kinetic rotational energy. The sub-functions accomplished by various components such as the bearings, armature, stator, terminals, etc., are well understood. However, when designing a motor, other aspects may come into play, as dictated by the requirements. How will excess heat be dissipated? How will the motor be protected from splashing liquids? How will the designer insure that flammable gasses will not be ignited? How will the motor be attached to some kind of structure? How will it be serviced? How long will it last? How much will it cost? These issues and the requirements that drive them are not altogether functional, and are not supported by existing function-based and other algorithmic theories of design.

Consider as a second example stacking chairs. A common feature of mass produced chairs is that they stack one on top of each other for compact storage and shipping. The requirement is that the chairs stack. But what is the function? And moreover, one chair is not capable of stacking. Stacking is a behavior that can only manifest with two or more chairs, and only with a user that is capable of lifting and stacking individual chairs. Current design theories do not support the satisfaction of requirements that are not functional, and are not well suited to artifacts in which the user interacts directly with the artifact as part of its operation. As Warell has stated:

> Methods are needed for the design of a larger variety of product aspects than is feasible with mechanical engineering design methodology of today. Design methods found within the European schools of design are inadequate for the design of products other than machine systems of transforming character. The reason for this is that the underlying theories only describe the nature of "operand-transforming" technical systems, and that the description of the process and function systems are too narrowly defined to be useful for the design of "non-transforming" products, or for products where the human is involved as an active user (Warell 1999).

According to the philosopher Thomas Kuhn, the existence of certain unresolved problems that current theories do not solve and phenomena that they do not explain indicates the possibility of a more advanced theory that solves these problems and explains these phenomena by introducing new concepts and overturning some assumptions or commonly held beliefs inherent in the old theory (Kuhn 1996). In the next section we delve into the theoretical underpinnings of the most prevalent schools of thought in design and show that they are all based on algorithmic concepts such as function, which imposes significant artificial limitations to the explanatory power of these design theories and the problems they can solve. In Sect. 3 we outline what a relational design theory should encompass based on the concept of entanglement and a relational model of design previously espoused by the authors, and propose the concept of affordance as a relational concept that handles the entanglement between the elements of the relational model of design. In Sect. 4 we further explain the concept of affordance and contrast it with the concept of function. In Sect. 5 we develop a framework for Affordance Based Design. Finally in Sect. 6 we return to the motivating examples in order to demonstrate the explanatory power of the relational theory of Affordance Based Design.

2 Review of existing design theories

2.1 Design as an "artificial science"

The history of modern engineering design theory and methodology begins with the introduction of Herbert Simon's revolutionary book The Sciences of the Artificial (1996, originally published in 1969). Before that, *engineering design* was largely synonymous with *analysis*, i.e., determining the dimensions of parts based on the analysis of forces, stress, fatigue, etc. Any other activities associated with design, such as coming up with a working concept, were considered art and not science. Indeed, in many circles, the word *design* still connotes *art*, such as fashion design of clothing, interior design of houses, and even the industrial design of consumer products. Simon's work revolutionized the study of engineering design by laying a theoretical basis on which a broader array of design activities could be considered scientifically—bringing them out of the hazy ambiguity of art and into the sharp focus of science. Indeed, other authors [most notably Dixon (1966)] had pointed to the need of studying broader aspects of design scientifically. Simon did this by showing that much of design has to do with information processing, something at which he also showed the human mind is particularly adept. Simon recognized that the same general design procedure of information processing could yield either an engineered product, or architectonics, or a business organization, or a musical score. Any of these creations of man were by definition *artificial* and the study of how one creates such artificiality is the title of his book. Design is the central activity, which again, crosses a variety of domains. Design is admissible to scientific inquiry because we can study how the relevant information can and should be processed. Thereby Simon's work served as an initial call across academia that design should be studied and taught.

Many other important ideas were introduced in The Sciences of the Artificial, including chunking of memory, representation in memory, cognitive psychology, complexity in the environment, and function in artificial systems. Simon argued that the complexity observed in behavior (his example is the circuitous path of an ant over uneven sand) is a direct reflection of the complexity of the environment (the uneven sand), i.e., that the underlying mechanics driving that behavior (in the ant) were much simpler than the environment, and thus those mechanics (in the ant, or by extension in the human mind and brain) could be studied scientifically. Once most of the complexity of behavior (not of the biological organism) had been lifted from the person to the exterior environment, the mechanics of the organism's behavior could be studied in *functional* terms. The idea being that we could describe the (fairly mechanical) behavior of a (biologically complex) organism in terms of its function (what comes in with respect to what goes out) without any obligation of describing the messy details of what is actually going on inside. Moreover, we can reproduce the same behavior on an artificial system (i.e., on a computer) using a radically different internal structure (such as a programming language) so long as the functional relationships remain the same. And certainly, if we can describe complex organisms functionally, then so too can we describe artifacts functionally.

It is worth examining at this point what the concept of function means in engineering design. Many authors have posed definitions for function; several of these are shown in Table 1 (emphases added).

From the above definitions it is evident that the concept of function denotes what an artifact is *intended* to do (cf., Dennett and Haugeland 1987). The concept of function also denotes *action*: the *transformation* of some input state to an output state. As discussed in Sect. 1, this presents a problem of description for objects which have an obvious use, but no active function transforming inputs to outputs (including static structures such as stools, chairs, and bridges, or many other artifacts typically having few moving parts, such as ladders, athletic gear, display screens, packaging, nuts and bolts, pulleys, etc.) Otto and Wood's definition also refers to the fact that in design theory functions are usually considered to be form independent. As discussed in Sect. 4, this limits in practice the ways the concept of function can be used to solve design problems.

2.2 The Pahl & Beitz framework, its variants, and their basis in function

Following Simon, the next milestone in engineering design research is the familiar book Engineering Design: A Systematic Approach (Pahl et al. 2007; first published in German in 1977). The basic premise of the Pahl & Beitz (P & B) framework is that design should be executed as a structured systematic activity, as opposed to the ad-hoc fashion it had been practiced previously. In order to systematize design, the authors decompose design into several stages. Within each stage, particular methods are presented for executing particular tasks, such as ideation methods, decision methods, design-for-x methods, etc. However, besides fitting within the overall P & B framework, these particular methods share no common theoretical basis. Rather each method is accepted because it produces effective results, not because it is based on any particular theory.

At least two important theoretical antecedents can be identified for the P & B framework. One is General Systems Theory which describes systems in terms of their external boundary, inputs and outputs across that boundary, and internal organization (cf., Bertalanffy 1969). This leads to the modeling by P & B of artifacts as generic systems with boundaries and inputs and outputs of material, energy, and information. Pahl and Beitz discuss the influence of Systems Theory on their work explicitly (Pahl et al. 2007: 14–15). The second theoretical predecessor, as discussed above, is the function based work of Simon, and various German authors, especially Roth (cf., Roth 1986). The functional approach is in fact very compatible with systems theory and Pahl and Beitz combine general systems modeling with functional modeling to model artifacts in a hierarchy of subfunctions sharing flows of material, energy, and information. The essence of the P & B "clarifying the task" phase of design is establishing a high-level functional decomposition with associated flows. The conceptual design phase is concerned with identifying working concepts to accomplish each function. This is followed in the embodiment phase by specifying physical attributes embodying each concept to perform each function. Finally in detail design only the details remain, such as tolerances, material compositions, surface finishes, manufacturing considerations, etc.

During the late 1980s and continuing to today, various English language authors adopted the high-level function based systematic approach of Pahl and Beitz, complementing it with their own more specific research. Among these are texts by Cross, Pugh, Dieter, Ullman, Ulrich and Eppinger, Dym, and Otto and Wood. There remain several schools of thought in design science, however, that are sufficiently different to warrant individual discussion.

2.3 Decision based design and its algorithmic character

Another school of thought in design which shuns, as Simon did, the "cookbooky" (to use Simon's term) heuristics that have characterized much of design practice is Decision Based Design (DBD), which espouses the view that *design is decision making*. As a leading proponent of this view has stated, "the underlying concept behind this theory is the

Table 1 Several definitions of "function"

Author	Definition of function
Webster's (Guralnik 1984)	"The normal or characteristic *action* of anything"
Akiyama (1991)	"… refers not to static, fixed, or apparent facts, but to the *actions*, or workings, of dynamic, interdependent, process-oriented things"
Pahl et al. (2007)	"*The general input/output relationship of a system whose purpose it is to perform a task*"
Ullman (2002)	"*What a device does*; *the desired output* from a system"
Chandrasekaran and Josephson (2000)	"The idea of a machine, system or a person *doing* something or having a property that is *intended* or *desired* by someone, or deemed appropriate from someone's point of view"
Otto and Wood (2001)	"A clear, reproducible relationship between the available *input and the desired output* of the product, *independent of any particular form*; what the product *does* to satisfy the customer"

basic notion that engineering design is a decision-making process" (Hazelrigg 1996: xix). Accordingly, if one wants to understand design, one ought first to study how best to make decisions, which is the province of several fields of mathematics, which Simon himself listed off: optimization techniques, utility theory, statistical decision theory, means-end analysis, and cost-benefit analysis (Simon 1996: 118). This list reads very similar to the table of contents for the aforementioned design textbook based on the DBD approach (Hazelrigg 1996). The principal advantage of such an approach to design is its mathematical rigor. Thus, advocates of DBD can and do claim superiority over other methods in design that do not possess such rigor, such as Pugh selection matrices, the Analytic Hierarchy Process, and Quality Function Deployment.

Decision Based Design has therefore become synonymous with the study of mathematical decision making in design, particularly the application of Utility Theory. However, the "basic notion that design is a decision-making process" may be too strong. In fact the implementation of this assertion in DBD departs starkly from one of Simon's main ideas, which was that human decision making is not altogether rational. Simon argued famously that human decision makers stop at "satisficing" solutions rather than traversing the exhaustive process of seeking optimum solutions (Simon 1996: 27–30, 119–121). By contrast, Utility Theory (as used in DBD) is a mathematical framework in which to maximize utility given known customer preferences—not to satisfice, but to find an optimum.

Decision making is certainly important, as many authors including Pahl, Beitz, and Pugh have acknowledged, but as they have more thoroughly discussed, design must include many other activities pertaining to both early stages of design (in essence, determining what should be created and what the alternatives are) and the latter stages of design (pertaining to details over which the designer at that point has little choice). It is dangerous to assume that mathematically rigorous theories for decision making are sufficient to encompass all of design. The obvious limitation of DBD is that it only extends to decision making, and not, for example, ideation. The more subtle limitation is that the decision making that DBD encompasses is entirely algorithmic, which thereby asserts that design, as decision making, is fundamentally algorithmic. It is this fundamental limitation with which we disagree and intend to overcome with a relational theory of design that is not algorithmic.

2.4 Axiomatic design, its basis in function, and lack of evidence thereof

Whereas the previously discussed schools of thought in design have been grounded in the views of Simon, that design is an artificial science and thus subtly different from the natural sciences, another school of thought views design science as being no different. The view of axiomatic design (Suh 1990, 2001) is that all sciences are based on axioms. Suh defines axioms as "truths that cannot be derived but for which there are no counterexamples or exceptions" (Suh 2001: 7).

The spirit of axiomatic design is very much in tune with the spirit of DBD, that is, to shun heuristics in favor of a mathematically rigorous framework. Thus from its two fundamental axioms, axiomatic design derives theorems and corollaries as guidelines for design.

However, such a view of science as being axiomatic is not in harmony with the traditional scientific method, which prescribes that hypotheses be based on observations, and hypotheses tested by experiment, and only after successful testing are hypotheses considered scientific theories. In contrast, the dictionary defines an axiom as:

1. A statement universally accepted as true; maxim
2. An established principle or law of a science, art, etc.
3. *Logic, Math.* A statement that needs no proof because its truth is obvious; self-evident proposition (Guralnik 1984).

Euclidean geometry, for example, is based upon five axioms postulated by Euclid. Other equally valid geometries exist based upon different axioms (such as Riemannian geometry). Hypotheses about design are capable of being tested, and hence either supported or rejected. Therefore, the standard scientific method can be applied to design science and there is no need to resort to axioms. To the extent that any "law of science" becomes an axiom is only *after* that law has been investigated by the standard scientific method and *after* it has become established by those means.

Suh states in his second book that "The design axioms were created by identifying the common elements that are present in all good designs" (Suh 2001: 9). But in his first book, Suh cites only five initial design projects that were considered (Suh 1990: 20). Therefore, the claim that the two axioms are present in "*all* good designs" seems to be far too strong. A more pertinent and unanswered question is how many designs have actually been considered. Moreover, it is unclear who is to judge (and how) what constitutes a "good" or a "bad" design. To claim that the design axioms are axioms removes their proponents from the need to provide any evidence supporting them. Using the standard scientific method, the two axioms should not properly be called axioms, but rather hypotheses, and to derive theorems and methods based on them is a premature exercise at best. It is to be noted, however, that axiomatic design has now been taught and utilized for almost two decades and therefore a body of empirical evidence is now accumulating that support the efficacy of the methods.

Another objection to axiomatic design is that the two axioms do not capture all of what is empirically known or even relevant to design. Even if the two axioms are correct, and if everything derived from them is correct, then whatever follows from these two axioms is only applicable to the domains described by the axioms—specifically, functional requirements and information content. Similar to DBD, these axioms do not capture other aspects of design which are also important, such as the human aspects of design, including how designers do and should think, how people collaborate in the design process, how people interact with artifacts, etc. Thus in the axiomatic approach we find no guidance on topics such as creativity methods, collaboration methods, human factors or ergonomics issues, aesthetic qualities, industrial design, detail design, etc. They are outside the scope of axiomatic design.

It is interesting to note that like the P & B framework, axiomatic design is at its core still functional, making explicit use of functional modeling and decomposition. Because the design axioms are based on the existence of "functional requirements," they provide no theory as to why a functional approach is appropriate or sufficient. In effect, in order to accept the design axioms as true, we must first assume that the concept of function is sufficiently powerful to be used as a fundamental concept in design. Functional Requirements are defined as the (emphases added) "minimum set of independent requirements that completely characterize the *functional* needs of the product in the *functional* domain" (Suh 2001: 14). If all the functional requirements capture are *functional* needs, then the design will not be completely or satisfactorily characterized in general, since not all requirements are functional in nature (e.g., cost, aesthetics, recyclability, etc.) Ironically, this fact cannot be escaped even in the axiomatic approach where many "functional requirements" are not functional at all, for example "Quality" and "Innovation" (which could more properly be considered the subjective metrics) in Suh's example of "the four domains of an Academic Department" (Suh 2001: 13).

2.5 Common features of existing design theories and opportunities for theoretical development

To this point the essential theoretical contributions of Simon, Pahl and Beitz, Hazelrigg, and Suh have been discussed. Now several common features as well as open research areas can be recognized across all or most of these published works. The first common feature, which leads to an open research direction, is in terms of theory. Beyond the original contribution of Simon that design be studied as an artificial science, and beyond the contribution of Pahl and Beitz, that design be practiced systematically, there has been little fundamental theory developed. The effective methods presented by a variety of authors do not share a common theoretical basis outside of their placement within a larger systematic framework. To again invoke Simon's term, much of engineering design remains "cookbooky."

The second common feature, which leads to another research area, is the wide use of the concept of *function* in design. This idea, as has been shown, dates back at least four decades to the work of Simon, Roth, and others. However, *there is no underlying theory as to why we ought to consider function as the most fundamental aspect of engineering design*. To wit, there is no theory to guide us as to the proper use of function in design, what its limitations are, and what underlying assumptions there might be. Function has in effect been accepted as the de facto fundamental concept in design without theoretical justification. For example, in their work on a functional basis for design, Stone and colleagues explicitly assume that a functional description is sufficient and complete. They state "in engineering design, the end goal is the creation of an artifact, product, system, or process that performs a function or functions to fulfill customer need(s)" (Hirtz et al. 2001, 2002).

Similarly, Chandrasekaran and colleagues, in their work on function in engineering design, state: "Design exists in order to deliver artifacts that have desired functionalities. The concept of function is thus fundamental in engineering practice. Engineers' intuitive understanding of this concept has, until recently, been sufficient for the practice of engineering" (Chandrasekaran and Josephson 2000). A similar assumption about function is evident in the work of many other researchers. This bias toward function precludes any exploration of concepts or modes of description that are not functional in nature.

It is worth noting that other common features which revealed open research areas in existing design theories have been recognized by other researchers and investigated successfully. One such common feature was the separation of design and manufacturing; this has been remedied in large part by the development of *concurrent engineering*. Another common feature was the tacit assumption that only one person was in charge of the design activity; this has been remedied in part by investigation into *collaborative design*. A third common feature was the assumption that only one product was being developed at a time, and from scratch; this situation has been addressed by researchers in variant design, modularity, product family design, and product platform design. There is ample reason to believe, therefore, that the two common features and research areas so far identified in this paper, that of a lack of sufficient theory and an over-reliance on function, can be successfully remedied by the application of novel concepts and research.

3 Building a relational design theory

3.1 Entanglement

In the previous section we have argued that one of the problems of current design theories is that they are built around the transformative processes of functions and algorithms, which prevents these theories from explaining or helping engineers to design aspects of systems which are non-transformative, such as human interaction, cost, aesthetics, and meeting other so-called non-functional requirements. But what kind of theory can be developed that does not rely on such transformative processes? We can look to a number of other fields in which such non-transformative theories have been developed, known as relational theories.

Let us first consider the domain of computer science. For many years the archetypal example of a transformative system in computer science is the Turing Machine, a purely predicative formalism that executes an algorithm [as Turing proved, *any* algorithm (Turing 1959)] with perfectly predictable results.

By contrast, a relational system in computer science does not operate on a given input, but rather takes the unpredictable input of a human user. These systems are called Interaction Machines by the computer scientist Peter Wegner who has produced a mathematical proof that Interaction Machines are more powerful than Turing Machines (Wegner 1997, 1998).

Wegner showed the completeness of algorithms (expressed on Turing machines) and the incompleteness of interaction (expressed on Interaction Machines.) Incompleteness of human interaction follows from the unpredictability of human input, which is modeled by infinite series which are by definition incomplete (because they are infinite). Thus Wegner proved that interaction is a larger, non-formalizable computing paradigm than standard Turingesque closed algorithms. Transformative processes begin to fail (i.e., are not powerful enough) in design in the same way that they begin to fail (i.e., are not powerful enough) in computing, when human interaction is introduced, which is unpredictable by nature.

Wegner's proof structure is based explicitly on the proof structure of the mathematician Kurt Gödel, who proved the incompleteness of formalisms of number theory (Gödel 1931). Gödel's proof shows how any formalism of number theory can be made to produce contradictory results: by referencing features of the number theory itself. This kind of self-reference leads to *entanglement*.

The same situation occurs in physics, where the actions of quantum particles depend on the actions of their observer. A similar situation occurs in standard Newtonian physics in the n-body problem, where a solution of the trajectories of multiple bodies acting under mutual gravitational attraction is not achievable in closed form. Another similar situation occurs in philosophy in Epimenide's paradox "This statement is false" which exposes the limitations of statements about truth: when they refer to themselves. Gödel's theorem shows us that such entanglements are essential features of reality. Wegner's theorem shows us how the power of such entanglements can be harnessed in artificial systems.

In design, the entangled relationship between people and artifacts is inescapable, because artifacts are always designed for human use, usually designed by humans themselves (using computers and other tools), and situated within a larger context of a complex world economy. Some consequences are individual differences between consumers and designers, changing mindsets, preferences, needs, and attributes of all these people, non-rational unpredictable behavior, and creativity. Cast in this light, it is quite understandable why approaches to design based on transformative processes fail to explain or give guidance for designers in many situations. The alternative, suggested from these considerations, is a relational paradigm for design based on a non-transformative concept.

3.2 A relational model of design

From the above relational theories and models, a relational model for design can be formulated by specifying the entities of interest and the relations between them. To wit, let us define the scope of our relational model by assuming that fundamental to any design activity are three entities: the designer of the artifact, the artifact being designed, and the user of the artifact.

In general, any or all of these entities can be non-singular. Multiple designers can be involved (i.e., collaborative design), multiple artifacts can be designed at once (i.e., product family design), and multiple users may use the artifact (i.e., in mass production). In general the relationships are that (1) The designer designs the artifact, and (2) The user uses the artifact. However, these relationships are entangled, because the designer determines how the user uses the artifact through the structure of the artifact itself. Moreover, how the designer designs the artifact is motivated in part by the users' own demands and wishes. In other work (Maier and Fadel 2006) we have developed a relational model for design based on the above entities and relationships: the designer–artifact–user (DAU) system, shown graphically in Fig. 1. An important result is that this formalism is also a complex adaptive system (CAS) following the same cycle as other CAS (cf., Gell-Mann 1994).

In order to build a relational theory for design, we need a concept that will enable us to address the interactions between designers, artifacts, and users. In other words, we need *a relational concept for design*. As discussed above, the transformative concept of function is not sufficient.

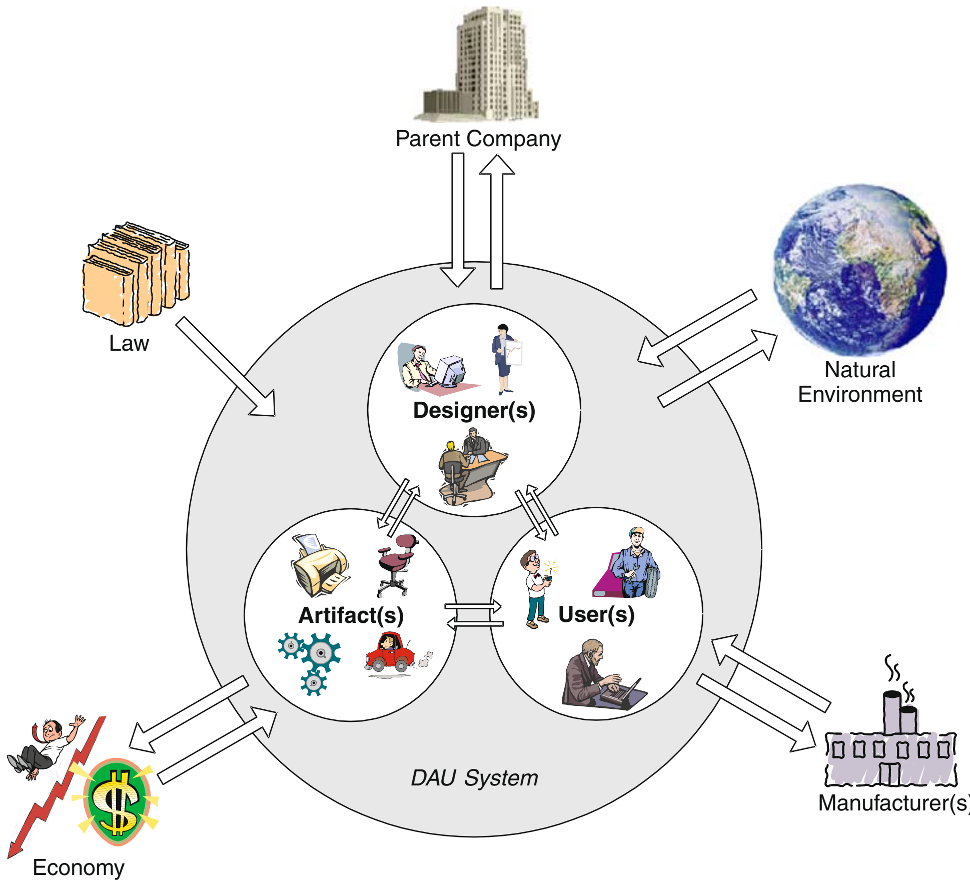

Fig. 1 Generic situated designer-artifact-user (DAU) system

We could invent a new relational concept for design if necessary. However, such a relational concept already exists. It is the concept of *affordance* introduced in the field of perceptual psychology (Gibson 1979). Briefly stated, an affordance is what one system (say, an artifact) *provides* to another system (say, a user). The concept of affordance is relational because of the *complementarity* entailed between two interacting systems.

Gibson explained the concept of complementarity further himself (all emphases are his):

> As an affordance … for a species of animal, however, they have to be measured *relative to the animal*. They are unique for that animal. They are not just abstract physical properties… So an affordance cannot be measured as we measure in physics… An affordance is neither an objective property nor a subjective property; or it is both if you like. An affordance cuts across the dichotomy of subjective–objective and helps us to understand its inadequacy. It is equally a fact of the environment and a fact of behavior. It is both physical and psychical, yet neither. An affordance points both ways, to the environment and to the observer… Affordances are properties taken with reference to the observer. They are neither physical nor phenomenal (Gibson 1979: 127–128).

In other words, an affordance depends on both the artifact (Gibson's environment) and the user (Gibson's animal), or—in our generalization—any other two interacting systems. The relationship is not independent of either. This may be contrasted with a transformation process like an algorithm or function, which is a fixed process no matter what the input—always delivering expected outputs for given inputs.

As a relational concept, the idea of affordance allows us to describe the relationships between designers, artifacts, and users in design. The nature of the relationship between artifacts and users is that artifacts are used by users (which is obvious), but it is the affordances of the artifacts that determine *how the artifacts can be used* (which is *not* obvious). The nature of the relationship between designers and artifacts is that designers create the affordances of artifacts. They specify all the properties (geometries, dynamic behaviors, colors, etc.) that will afford a certain set of uses to a certain set of users. Thus the nature of the relationship between designers and users is that designers must ascertain from users a target set of affordances. Conversely, the users inform the designers of desired uses—what they want the artifact to afford. Taken together, these relationships define the entanglement between designers, users, and artifacts, as shown by the circularity (cf., the cycle of other similar CAS discussed by Gell-Mann 1994) in the DAU system in Fig. 1.

4 Further explanation of the idea of affordance

4.1 Some history

The theory of affordances was first put forward by the perceptual psychologist James J. Gibson (1979). Although the term has its roots in concepts from Gestalt psychology (cf., Koffka 1935), Gibson coined the English word "affordance" as follows (all emphases are his):

> The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill. The verb *to afford* is found in the dictionary, but the noun *affordance* is not. I have made it up. I mean by it something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment (Gibson 1979: 127).

The concept of affordance is perhaps most easily understood through some simple examples. Gibson gives the following examples:

- "If a terrestrial surface is nearly horizontal (instead of slanted), nearly flat (instead of convex or concave), and sufficiently extended (relative to the size of the animal) and if its substance is rigid (relative to the weight of the animal), then the surface *affords* support"
- "Terrestrial surfaces, of course, are also climb-on-able or fall-off-able or get-underneath-able or bump-into-able relative to the animal. Different layouts afford different behaviors for different animals"
- "Other animals afford, above all, a rich and complex set of interactions, sexual, predatory, nurturing, fighting, playing, cooperating, and communicating"
- "Air affords breathing, more exactly, respiration. It also affords unimpeded locomotion relative to the ground … when illuminated and fog-free, it affords visual perception. It also affords the perception of vibratory events by means of sound fields and the perception of volatile sources by means of odor fields"
- "Water … affords drinking. Being fluid, it affords pouring from a container. Being a solvent, it affords washing and bathing. Its surface does not afford support for large animals with dense tissues"
- "Solids afford various kinds of manufacture, depending on the kind of solid state. Some, such as flint, can be chipped; others, such as clay, can be molded; still others recover their original shape after deformation; and some resist deformation strongly" (Gibson 1979).

Gibson's book The Ecological Approach to Visual Perception is most concerned with how animals perceive their environment, which Gibson argues is through the perception of affordances in the environment. As such, Gibson's theory of affordances is a *descriptive* formulation: it describes how animals perceive their environment. Since Gibson's introduction of affordance theory and his ecological approach in general, the concept of affordance has been the subject of much study and application within perceptual psychology (see, e.g., Warren 1984; Riccio and Stoffregen 1988; Heft 1989; Mark et al. 1990; Turvey 1992; Oudejans et al. 1996; Sanders 1997; Zebrowitz and Collins 1997; Bingham 2000; Gibson 2000a, 2000b; Lintern 2000; Pickering 2000; Stoffregen 2000). It is precisely this body of experimental evidence and application in practice that grounds the concept of affordance as an established theory that is mature enough to apply to the field of design.

A decade after Gibson seminal work, another psychologist, Donald A. Norman, took Gibson's theory of affordances and extended it into a *prescriptive* formulation: Norman gives some guidelines as to what certain objects should afford and should not afford. However, Norman, in his book The Psychology of Everyday Things, also published as The Design of Everyday Things (Norman 1988), is concerned primarily with, as the title says, "everyday things" and not the design of artifacts in general. Hence Norman's theory culminates in two design-for-x methodologies (design-for-usability and design-for-error) but stops short of incorporating the concept of affordance as fundamental to the design of *any* artifact.

Norman gives several examples of affordances of everyday objects:

- "A chair affords ('is for') support and therefore, affords sitting. A chair can also be carried"
- "Glass is for seeing through, and for breaking"
- "Wood is normally used for solidity, opacity, support, or carving"
- "Flat, porous, smooth surfaces are for writing on"
- "Plates are for pushing"
- "Knobs are for turning"
- "Slots are for inserting things into"
- "Balls are for throwing or bouncing" (Norman 1988).

Norman and others have further refined his approach with respect to *interaction design* [which includes graphical user interfaces (GUIs) as well as human–computer-interaction (HCI) in general] (Gaver 1991; Norman 1999; St. Amant 1999; McGrenere and Ho 2000; Hartson 2003).

In a similar vein, *Ecological Interface Design* (Vicente and Rasmussen 1990) emphasizes high-level processing of data by human users and speaks chiefly to the layout and configuration of displays. Meanwhile, Warren (1995) and his students have applied the concept of affordances to design specific artifact–user relationships, such as the height of stair treads. An excellent summary of the ecological approach to physical interfaces and prospects for the future is given by Pittenger (1995). A more detailed treatment is offered in a collection of articles edited by Flach et al. (1995). More recently, some researchers in computer engineering have used an affordance based approach to design "usable and intuitive physical interfaces" for computing devices (Sheridan and Kortuem 2006).

Inspired by the work of Norman, some researchers in the industrial design community have also adopted the concept of affordance as a psychological tenet underpinning *product semantics* (Bush 1989; Krampen 1995; Krippendorff 1989, 1995). Product semantics is defined as the "study of the symbolic qualities of man-made forms in the cognitive and social contexts of their use and application of the knowledge gained to objects of industrial design" (Krippendorff 1995). A concise review of the use of affordance in this field as opposed to its use in HCI is given by You and Chen (2007).

The idea of affordance has also been applied in the field of artificial intelligence, e.g., how to design robots that recognize affordances in their environment (Murphy 1999). The application of the theory of affordances to engineering design has been advocated by the present authors in a recent series of papers (Maier 2005; Maier and Fadel 2001, 2002, 2003, 2005, 2007, 2008; Maier et al. 2007; Gaffney et al. 2007). As was our intent, the presentation of these ideas has recently sparked some debate and usage within the larger engineering design research community (e.g., Brown and Blessing 2005; Galvao and Sato 2005, 2006; Galvao 2007; Kim et al. 2007).

4.2 Remarks on properties of affordances and differences with function

The first important property of affordance, which defines its relational character, is complementarity, as discussed above. In Gibson's definition of affordance, he said that it "implies the complementarity of the animal and the environment". This is important in design, because we are particularly interested in the *complementarity*, or in other the words, the entangled relationships, between certain animals (designers and users) and certain things in their environment (artifacts).

Another implication of complementarity is that the affordances depend on specific users, although those users can sometimes be conveniently organized in groups. Thus an artifact can afford different behaviors to different users. For example, a door handle may afford pulling and thus opening of the door to an adult, but not to a child who cannot reach it. A flat written sign can afford communicating information to sighted people, but not to the blind.

Gibson also discussed the *polarity* of affordances, stating that affordances can either be for good or for ill. *Positive affordances* are potentially beneficial to the user, while *negative affordances* are potentially harmful. For example, a positive affordance of an automobile is providing transportation to users, while a negative affordance of an automobile is producing pollution that is harmful to users. To state the obvious, designers must be careful to design desired positive affordances without introducing harmful negative affordances. However, this is a shift in mind-set from current design theories that emphasize achieving functionality, but do not actively seek to protect users from harmful effects.

A system can also possess a *multiplicity* of affordances. For example, Gibson mentions that water affords drinking, pouring, washing, and bathing. Gibson also discussed the many affordances that other animals provide. Note that of the many affordances an object can possess, some may be positive and some may be negative, because of *polarity*. Automobiles, for example, afford transportation to passengers, but also danger to pedestrians. Again, there is a distinction here from current design theories based on function which, following the P & B framework, seek one embodiment per function.

Although a system may possess an affordance, there is still room to describe *how well* the system affords that specific use or behavior in terms of *quality*. For example, Norman points out that a chair affords both sitting and carrying. However, chairs in general afford sitting better than they do carrying. Similarly, a briefcase also affords sitting as well as carrying (as well as other things, such as transporting documents) but a briefcase affords carrying much better than it does sitting. Again there is a distinction with the concept of function here. It is a bit awkward to describe the quality of functions because either inputs are transformed to outputs or they are not. Affordance based design forces a shift in thinking that emphasizes the conscious design of the quality of each affordance.

Another difference between the concepts of function and affordance is the role of form. Whereas functions and functional decomposition are form *independent* (a variety of forms can perform the same function), affordances are form *dependent*. By definition, it is the form (i.e., structure) of artifacts that determines what they afford to specific users. An interesting concept that helps to explain this difference is the idea of "wirk elements". Jensen

(2000) defines a *wirk element* as a "functionally active form element that is part of an organ and contributes to the realization of a function". This definition is based on an earlier use of the term by Rodenacker (1970) who states "wirk elements may primarily be surfaces being built by technical parts". The idea here is that functions are not fundamental, but can be decomposed into the physical surfaces that interact in order to effect a particular function. According to this view, a function cannot be fully explained without reference to its physical embodiment. If we characterize the *provision of a function* as an affordance, then the design of this affordance will of course require the specification of the necessary artifact structure.

5 Framework for affordance based design

5.1 Artifact–user affordances

Recall that affordances describe a potential behavior between two or more subsystems within a larger designer–artifact–user complex system. In previous work (Maier and Fadel 2001, 2002, 2003) we have found it helpful to distinguish between two broad categories of affordances for engineering design based on whether the subsystems that are interacting are an artifact and a user, or two artifacts, i.e., artifact–user affordances, and artifact–artifact affordances. An *artifact–user affordance* expresses an interactive relationship between an artifact and a user where a behavior may occur between the artifact and user that neither the artifact nor the user could manifest alone. Take for example Norman's example of a user sitting in a chair—the artifact–user affordance being "sit-ability".

Note the total set of interactions and relationships between user and artifact is larger than the subset that are affordances. *The distinguishing feature of artifact–user affordances is the potential usefulness of the artifact to a user*. I.e., the artifact is providing a use to the user. Hence, as Gibson pointed-out, typical physical properties such as mass, texture, color, transparency, etc. are not, in and of themselves, affordances. But only to the extent that these properties are useful in some way to the user does an affordance exists. Thus we can define an *artifact–user affordance* as an interaction between artifact and user in which properties of the artifact offer a potential use to the user. The artifact is then said *to afford* those uses to the user.

Another distinct but related set of interactions between artifact and user occurs when the user actually uses the artifact. These are behaviors, and not affordances. For example, the affordance of drivability of an automobile is one type of interaction, while the act of a person actually driving is a different type of interaction, but the two are related because the automobile must first afford driving (an affordance) before it can ever actually be driven (a behavior).

5.2 Artifact–artifact affordances

Consider again the motivating problem of designing stacking chairs. There are two affordance relationships here. One affordance is between the chairs and a user. The chair must afford stacking *to a user*—the user must be able to pick up a chair and stack it on another nearly identical chair. The second affordance is between two chairs irrespective of the user. The geometries of the chairs must be such that they fit down one on top of another. They must afford stacking *to each other*. This is an example of an artifact–artifact affordance, which is a potential behavior that may be exhibited by the two artifacts together, that could not be manifested by either artifact alone. E.g., stacking can only manifest with two or more chairs.

It is interesting to note that in the context of design, artifact–artifact affordances are usually designed in order to fulfill artifact–user affordances. This is obviously true in the case of stacking chairs, which users stack for their convenience of storage or shipping. Other examples can be found in the artifact–artifact affordances of two gears. When designed properly, potential behaviors of the two gears include turning, power transmission, noise generation, grinding particles, etc. All of these potential behaviors are artifact–artifact affordances which can be either designed for or against. The AAA of power transmission can be used by a designer of a vehicle to serve the AUA of affording user transportation, while the AAA of noise generation can be designed against to serve the AUA of affording a quiet cabin environment.

5.3 AUA and AAA in the context of DAU systems

In the context of the DAU complex system, artifact–user affordances (AUA) appear as interactions between the artifact and user subsystems, and artifact–artifact affordances (AAA) appear as interactions within the artifact subsystem itself. Interactions between the designer and user subsystems include the information needed to specify which affordances should and should not exist in the artifact under design. Interactions between the designer and artifact subsystems include the specification of the artifact's properties that determine its various affordances internally (i.e., AAA) and externally to the targeted users (i.e., AUA). These interactions within the DAU system are shown schematically in Fig. 2.

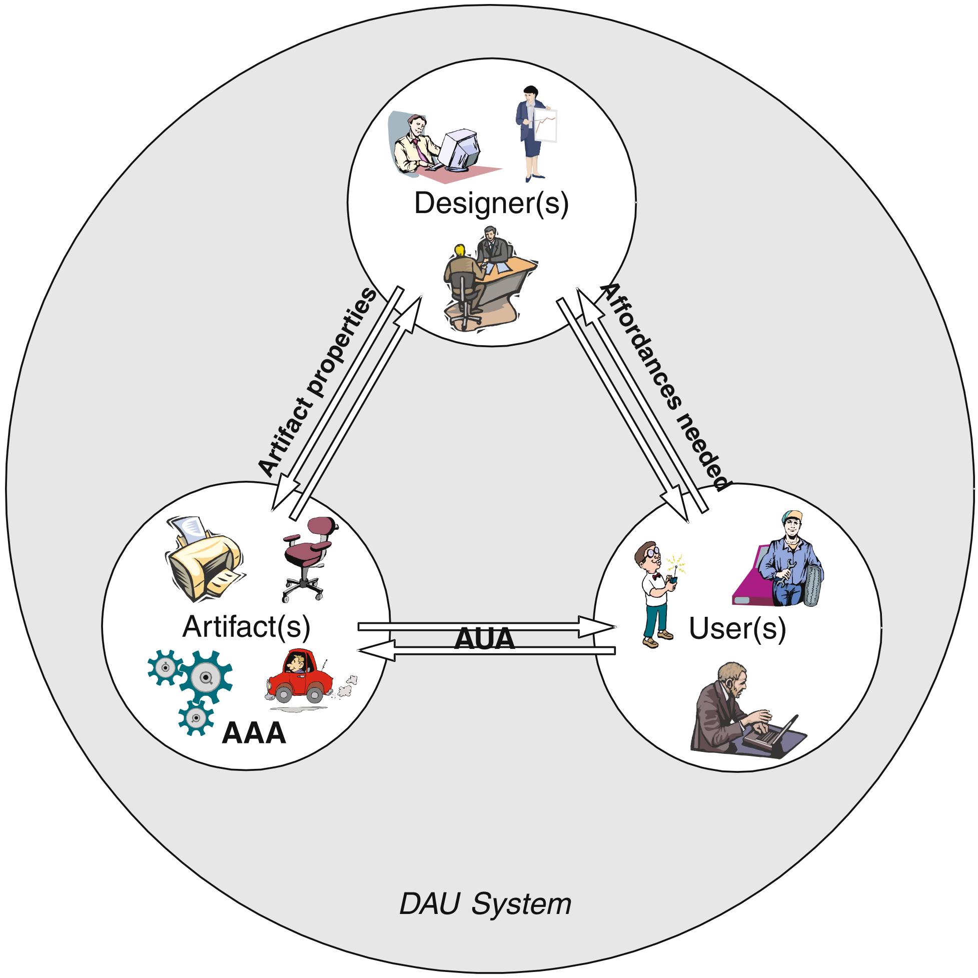

Fig. 2 Affordance related interactions within a designer–artifact–user system

5.4 Changing affordances

A major insight of what has been called "systems thinking" is the principle "structure influences behavior" (cf., Forrester 1968; Senge 1990). The concept of affordance can be used to better understand this principle by noticing that it is the structure of systems that determines their affordances, and the affordances describe what behaviors are possible, i.e.,

$$\text{structure} \Rightarrow \text{affordance} \Rightarrow \text{behavior} \quad (1)$$

Expression (1) also helps us to understand emergent behavior. Behavior "emerges" from the interaction of subsystems when the structure of those subsystems affords that behavior. However that behavior only manifests, or emerges, when the subsystems are allowed to interact.

What happens when we change the structure of a system (by accident or design)? Following expression (1), a change in structure propagates to a change in the system's affordances, which propagates to changes in behavior, i.e.,

$$\Delta\,\text{structure} \Rightarrow \Delta\,\text{affordance} \Rightarrow \Delta\,\text{behavior} \quad (2)$$

5.5 Application to design

Expression (1) describes *how structure influences behavior* in a system in general. Expression (2) states that by changing the structure of a system, designers can change the system's affordances. The affordances, in turn, determine how the system can potentially behave. Designers define the structure of a system, and thus its affordances, and thus how not only the artifact will behave (via AAA) but also how the user will behave with the artifact (via AUA). This suggests an affordance-based definition of design:

Definition Design is the specification of a system structure that does possess certain desired affordances in order to support certain desired behaviors, but does not possess certain undesired affordances in order to avoid certain undesired behaviors.

Using this definition, humans as well as computers may play roles in this specification process. However, human designers possess unique abilities that have not yet been matched by artificial means, for example the ability to create structure (i.e., ideation), knowledge about and empathy for how other humans will use an artifact being designed, etc. Certainly, particular design tasks can and have been automated (such as analysis tasks, information storage and retrieval, etc.), however, the above definition helps clarify the limited extent to which design may be automated in general. In particular, the vitally important determination of what exactly the artifact is supposed to afford and not to afford is an early and crucial phase of the design process itself. It is the responsibility of human designers and would be difficult to automate. It is also where customer needs and wishes must be brought into the design process.

The determination of affordances directly requires the expertise of designers who have knowledge of the context in which the artifact will be used (because of *complementarity*), including everything that will need to be done with the artifact (which leads to everything the artifact needs to afford), not only what the artifact will need to do itself (i.e., transform or function). Thus an important difference between affordance as a new view of the design process and other views of the design process is the formal identification of things that the design should *not* afford, especially with respect to identifying negative affordances of concepts during the design process, not just requirements to be met.

6 Examples of the explanatory power and potential innovation using affordance based design

6.1 The motivating example of the design of an electric motor

Let us return to the issues raised in Sect. 1 with regard to the design of an electrical motor, and attempt to resolve some of these issues using the relational theory of design developed thus far. As before, the function of the motor as a whole and its various components such as the bearings, armature, stator, terminals, etc. are well understood. However, due to electrical and frictional losses, several of the mechanical components produce heat, which must be dissipated in order for the motor to perform its intended function of transforming electrical energy to rotational kinetic energy. Thus a non-functional requirement (since no transformation is required) is that the motor must dissipate heat. One standard solution to this problem is to cast cooling fins onto the motor housing and attach a fan on the motor shaft which draws cool air across the cooling fins. The design of the cooling fins and fan blades is driven by known engineering science in terms of thermodynamics. A functional view of this design issue is that the cooling fins conduct heat, and that the fan pushes air. Air enters the system; hot air exits the system. But this "functionality" of dissipating heat is extraneous to the primary function of converting electrical energy to rotational kinetic energy. In fact the implementation of the functionality of dissipating heat is an exercise in mitigating a negative affordance of a particular choice of embodiments within the motor.

Another design consideration is that the motor may be in service where liquids are present, such as sea water, rain, or hydraulic fluid. The motor must be protected from these fluids in order not to short-circuit or contaminate the bearings—another non-functional requirement, since again, no transformation is required. A common solution to this problem is a sealed enclosure, a solution which tends to exacerbate the heat problem discussed above, since air is not allowed to circulate against the internal components. We could say the "function" of the enclosure is to protect the motor from liquid contamination. However, since the enclosure does not change the state of any inputs into outputs, it is somewhat of an abuse of terminology to say that the enclosure performs any function. Yet the enclosure does *provide* protection to the internal components; in other words the enclosure *affords* protection to the internal components. This distinction is not as superficial as it may seem, because it forces a shift in thinking. Just as the function of the motor is to convert electrical energy to rotational kinetic energy, while its embodiment also produces heat and is susceptible to damage by liquids, the "function" of the enclosure is to protect the internal components, while by virtue of its embodiment it also traps heat. Considering the affordances of these embodiments rather than just their function forces the designer to think about what else a particular embodiment affords besides providing its intended function (in particular the early identification of negative affordances).

It has been our observation that experienced designers intuitively perform this kind of analysis, routinely identifying problems with specific solutions, usually with reference to their physical embodiment, and attempting to remedy them during the design process. However this activity, which is crucial to a successful design outcome, is *not supported by current function based design theories*. Function based theories proceed from function to form, prescribing the functions that embodiments should have, and therefore stop short of analyzing any other relationships that the embodiments have. In contrast, affordance based design prescribes that designers analyze the affordances of each embodiment, and attempt to remedy negative affordances during the design process. For example, a change in the basic design of the motor, say from a wire wound stator to permanent magnets, may substantially decrease the amount of heat generated. We have discussed in greater depth elsewhere various methods using affordance based design; cf., Maier and Fadel (2003) for a discussion of methods; Maier and Fadel (2005) for an example application, and Maier et al. (2007) for a more advanced method. However, our focus in this paper is on the power of the underlying theory, and not the application of particular methods.

6.2 The motivating example of the design of stacking chairs

Returning now to our second motivating example: the problem of designing chairs to stack, the requirement is that the chairs stack. Again this appears to be a non-functional requirement since no inputs are transformed into outputs. Whether or not chairs stack depends on the specific geometry of the chairs; the chairs must afford stacking both to each other (an artifact–artifact affordances) and by human users (an artifact–user affordance), as discussed in Sect. 5.2. Two typical solutions to this problem are that either the chairs fold flat and then the flat chairs are stacked against each other, or that the chair does not fold and the seat is narrower than the legs, such that the legs of one chair can slip over the seat of another chair. Of course no obstructions such as exposed fasteners can be allowed to interfere with the stacking or unstacking operation, and adequate padding and spacing is needed to insure that stacked chairs do not damage each other.

These are not difficult requirements to meet, and indeed are typical of the kinds of practical constraints imposed on any real design problem. To the extent that such non-functional requirements are not encompassed by traditional function based design theories, in order to solve such problems designers must resort to ad-hoc methods. A key advantage of the affordance-based view of the design process is that it is not just limited to functions, or decision making, or any one particular area of design. Rather affordance based design allows designers to think about the design problem and all its requirements and all its embodiments and all of their ramifications within one conceptual framework.

Another requirement of the stair stacking problem is that the chairs must be stacked by people. As an artifact–user affordance, the design of the chair must be taken in reference to the capabilities of the human user who will be lifting and stacking the chairs. This is a clear example of the kind of *complementarity* that affordances capture, which again is not captured by a functional description nor supported by function based methods.

6.3 The example of a household ladder

As a final example, consider a household ladder (see Fig. 3a). From the standpoint of design theory we can ask what is the function of the ladder? It allows people to raise their elevation. Once again, there is no active transformation of inputs to outputs. It is easy to say that the ladder possesses the positive affordance of allowing people to raise their elevation, but one could also argue that the function of the ladder is to support load. Both statements would be correct. The question is which concept allows designers to handle more aspects of the design of the ladder. The ladder must allow people to raise their elevation, but it must also fold down for storage, and moreover it should be safe. The ladder shown in Fig. 3a has a problem in regards to this last requirement; there is a fundamental design flaw.

It is not safe to step on either of the two top steps or the horizontal brace (which looks like a step) on the rear of the ladder. However, the two top steps and the horizontal brace afford stepping. Clearly the designers recognized this design flaw, because molded into both the two top steps and the horizontal brace is a warning not to step on them (Fig. 3b). Hence this is a flawed design (regardless of the design patent and two other pending patents pertaining to the design). The ladder affords something it should not, something that is potentially quite dangerous—a *negative* affordance. A better, safer, higher quality design would incorporate the structural support of the two top steps and the horizontal brace without affording a place to step. Alternately, since the top step affords stepping, the ladder could be modified in order to make stepping on the top step actually safe, such as the ladder shown in Fig. 3c. In other work (Gaffney et al.

Fig. 3 Household ladder

2007) we have shown how the affordances of objects tend to improve over time whereas their function remains constant. We suggest that an earlier analysis of the affordances of a product should lead to more rapid product evolution.

7 Summary remarks

The idea of affordances is only three decades old, its application to engineering design only a few years old. Our interest is in pushing the frontiers of design theory forward through the application of this novel concept to design. We have shown previously how the designer–artifact–user system matches with other CAS. In this paper we have further differentiated the concept of affordance from the concept of function and emphasized the extent to which affordance based design forces a shift in thinking about design problems. This shift in thinking is comparable to the shift described by Kuhn when any new scientific theory is developed that introduces new concepts. Such a shift typically allows the investigator to account for additional phenomena, such as satisfying non-functional requirements and human interaction. However, new questions are inevitably raised, such as how to utilize the new concept in practice, and how to test it experimentally. We have suggested some methods for implementing affordance based design (Maier and Fadel 2003; Maier et al. 2007) and how to identify affordances (Maier and Fadel 2007), but because of the relational character of affordances, they are not as neatly implemented mathematically as transformative concepts. The development of affordance based design therefore continues.

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