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Reconciling Function- and Affordance-Based Design

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RECONCILING FUNCTION- AND AFFORDANCE-BASED DESIGN

By

Benjamin T Ciavola

A DISSERTATION

Submitted in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

In Mechanical Engineering-Engineering Mechanics

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This dissertation has been approved in partial fulfillment of the requirements for the Degree of DOCTOR OF PHILOSOPHY in Mechanical Engineering-Engineering Mechanics.

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1 ABSTRACT

Traditional engineering design methods are based on Simon's use of the concept function, and as such collectively suffer from both theoretical and practical shortcomings. Researchers in the field of affordance-based design have borrowed from ecological psychology in an attempt to address the blind spots of function-based design, developing alternative ontologies and design processes. This dissertation presents function and affordance theory as both compatible and complimentary. We first present a hybrid approach to design for technology change, followed by a reconciliation and integration of function and affordance ontologies for use in design. We explore the integration of a standard function-based design method with an affordance-based design method, and demonstrate how affordance theory can guide the early application of function-based design. Finally, we discuss the practical and philosophical ramifications of embracing affordance theory's roots in ecology and ecological psychology, and explore the insights and opportunities made possible by an ecological approach to engineering design. The primary contribution of this research is the development of an integrated ontology for describing and designing technological systems using both function- and affordance-based methods.

2 INTRODUCTION

The field of design theory is undergoing a period of change, in which both external and internal pressures are driving researchers to rethink long-standing assumptions about the nature and structure of the engineering design process. Pressure in the commercial environment has driven firms to seek competitive advantage through the adoption of agile and sophisticated design processes. Users and developers of traditional engineering design processes and design theories have fought to keep pace with these innovations, but in many ways their tools still lag behind practice. The central hypothesis of this dissertation is that there is an opportunity to bridge the innovation gap between theory and practice by providing design methodologists with a conceptual framework that addresses the shortcomings of traditional methods.

Design practitioners operate in a business environment driven by increasing global competition and an increasing pace of technology change. Businesses today operate in a globalized environment in which designers must work across and design for multiple cultures and socioeconomic backgrounds. The sheer variety of users, use contexts, and cultures that any product is likely to face mean that design processes must be responsive to a diverse set of user needs. While traditional techniques such as the House of Quality (Hauser and Clausing, 1988) provide formal tools for modeling the “Voice of the Customer,” these methods can be difficult to apply in the early stages of design because they depend on function-based problem and design decompositions (Maier and Fadel, 2009a).

Designers must also cope with the rapid pace of technology change both within and outside their companies. Technology selection and planning processes are forced to deal with Lean and agile practices, ever shorter design cycles, and consumers that expect rapid and continuous innovation. In this environment, the the key for business success has become less about the pursuit of high technology and more about the pursuit of appropriate technology. Designers must be able to account for how their products interface with, drive, and are driven by the ecosystem of other products in the marketplace. Traditional design methods focus on managing the logistics of technology development and the design of device functionality, and often lack tools for systematic analysis and design of human and technological interfaces.

Early-stage design is where the issues of globalization and technology change can be most efficiently handled. This is the point in the design process where the most influential decisions are made in terms of market strategy and commitment of resources, and the point at which firms have the most flexibility in the choices they make. While theorists and leading practitioners have developed effective tools to aid early stage design, most of these approaches are ad-hoc and rely on expertise instead of a strong theoretical foundation. While these processes are effective for solving certain kinds of well-defined problems, they assume a significant degree of maturity in the problem statement and lack a structured, robust, and theory-grounded approach to early-stage problem identification and requirements generation.

In an effort to handle some of these difficulties, the fields of design theory and design practice have undergone a degree of fragmentation. Design researchers have come to the conclusion that design is a complex process that includes but is not reducible to decision making, optimization, modeling, knowledge production, prototyping, ideation, and evaluation (Le Masson, Dorst, Subrahaiman, 2013). At the same time, design practitioners in a variety of disciplines have developed domain-specific design-for-X toolkits. While these toolkits provide an effective, modular approach to situationally incorporating best practices, their development was not guided by and their structures do not share theoretical foundations.

There is a compelling argument to be made that a lack of theory does not reduce efficacy in practice. However, the ability to deconstruct and analyze domain-specific design-for-X techniques and tools in a coherent, structured, and domain- independent fashion would allow design methodologists to systematically evolve processes to meet changing needs. For example, design methodologists should be able to take a toolset designed for high-volume industrial production, distill it to its essential components, and redeploy the technique for a low-volume production process in the developing world. This type of process would require the ability to identify commonality and variety in each design and manufacturing context and the ability to translate this knowledge into a new design process. Traditional engineering design theory lacks structured language and processes for coping with intra- and inter-contextual information of this kind, especially when it comes to reflexive analysis of design processes themselves.

In light of strong external pressures, internal divisions, and the breakdown of traditional aproaches, we argue it is prudent to expore adopting analyses and techniques from other fields. First, both historical and recent developments in the philosophy of technology provide a framework by which current weaknesses in design theory may be analyzed. Second, the ontologies and analytical frameworks of ecology in general and ecological psychology in specific provide the language and formalisms to address those weaknesses.

Our research strategy centers around developing a high-level framework able to unite the analysis of design methodology, design practice, and artifact use. To do this we investigate design processes and designed artifacts from the perspective of *technology* and *useful things.* We require an understanding of alternative approaches to understanding the nature of technology: its origins as a concept, its scope of applicability, and its implications for design. Second, we require an understanding of the structure of user needs: how they arise, what they are, how they can be described, and how those descriptions can be used to better drive traditional early-stage engineering design processes. Third, we require an approach for using our models of useful things and user needs to inform design methodology and the design process: identification of similarities exist between methods, what benefits there are to reap, and how design methodologists can achieve these goals.

In chapter 3 we begin our investigation of the nature of useful things through the len of design for technology change, continuing the work of Dr. Kiran Khadke. Dr. Khadke developed the Planned Product Innovation Method (PPIM), which uses function based product decompositions to identify, analyze, and organize technologies in artifacts and systems. By evaluating technologies along the dimensions of Performance Level, Principle of Operation, and Architecture, the PPIM guides the development of products and product platforms that are robust to different types of technology change. We extend the PPIM by developing tools for systematically identifying technological variants, where technological variants are designs that each use different technologies to achieve similar goals. The crux of this work lies in developing an approach to technology and an ontological framework capable of describing user and device requirements in a function-independent fashion. Based on the technology theory of Heidegger we find cause to adopt ecological psychology's affordance theory to extend the PPIM ontology.

In chapter 4 we attempt to fill in conceptual gaps identified in chapter 2. In the process of extending the PPIM with affordances, we we find that there is insufficient understanding of the relationship between the concepts of function and affordance. This lack of understanding has caused a rift between function- and affordance-based research, with each of the theories generally used to the exclusion of the other. Function theory has historically enjoyed a well-established position at the core of design theory, and more recent attempts to adopt affordance theory have adopted a strategy of presenting an alternative approach, including the development of entirely afforance-based design methodologies. We pursue an integration strategy with the goal of retaining the benefits of established function-based design processes while simultaneously gaining the flexible and expressive capabilities of affordance ontologies. We explore the structure and roots of both functions and affordances, and develop an action-theoretic approach to reconciling the two concepts. This approach brings the core concepts of the two philosophies together in a single conceptual structure with more descriptive flexibility and structure for the ‘fuzzy’ front end than function-based methods, and more applicability to established engineering design processes than wholly affordance-based methods.

In chapter 5 we further develop our approach to the integration of function and affordance with the development of a representational hierarchy and methodology that integrates an affordance-based early-stage design framework with an industry-standard function-based design method. The goal of this chapter is to clearly demonstrate the process for linking high-level affordance information with low-level function information in a practical design environment. We establish the utility of affordances for capturing high-level requirements in terms of user goals, plans, and actions, and present a technique for linking these goal- and action-based descriptions to low-level function-, behavior-, and structure-based device and system descriptions. The process for linking such descriptions is demonstrated through an automotive example. The outcome of this chapter is a technique for structuring the collection of design information throughout the design process based on a well-founded ontology of requirements.

In chapter 6 we explore the implications of a broader adoption of the affordance perspective by reflecting on its origins in ecology theory. We attempt to develop an ‘ecological’ approach to design theory that demonstrates the existence and importance of the totality of affordance relationships necessary for the creation of useful things. This ecological approach builds on prior work characterizing the existence of affordances of representational systems to explicitly expand the use of affordance concepts from the use-phase of artifacts to the design of artifacts by design practitioners and the design of design methods by design methodologists. We argue that an ecological perspective has the potential to provide a unifying framework for the analysis of the design process and development of design methodologies across all stages and fields of design. We argue that embracing the philosophical principle of realism provides a more sound and useful foundation for design theory than traditional approaches based on cognitive representationalism. The result of this is a framework for mapping, bounding, analyzing, and evolving individual design ecosystems.

This work seeks to address pressing contemporary issues in engineering design theory and design methodology through a process of conceptual and methodological reconciliation. Faced with an increasingly complex business and technological environment, designers, engineers, and their organizations are continuously innovating their design processes. Meanwhile, design methodologists and theorists have struggled to keep pace and account for the various approaches these practitioners have developed, resulting in a fragmented ecosystem of often incompatible design tools. Over the course of this document we attempt to construct a conceptual framework capable of accounting for these design tools and aiding their integration with contemporary approaches to early-stage design.

3 THE NATURE OF TECHNOLOGY[1]

Over the past few decades, modularity and product family design have emerged as key tools for the development of robust, evolvable, and successful products. These techniques have been used for such ends as mass customization, platform identification, design for manufacturability, and design for technology change.

This last – design for technology change – is an attempt to understand and predict how the rapidly evolving technologies that form the foundation of many of today's highly successful products evolve over the course of a product's lifetime. This 'over-time' perspective can be contrasted with the 'in-time' perspective wherein one designs a product for a specific, currently-existing set of technologies without regard for their future evolution. The over-time perspective, when coupled with module- and platform-design methods, provides the designer with an understanding of which subsystems rely on technologies that are likely to change over the course of the product line's multi-generational lifetime, the nature of those changes, and how to best architect the system to minimize unwanted deleterious interactions. In short, the goal of design for technology change methods is minimizing the cost of evolving a design as new technologies are introduced to keep pace with research, development, and market evolution.

The Planned Product Innovation Method (PPIM) (Khadke and Gershenson, 2008) was developed to aid in the development of products and product platforms that are robust to technology change. It clusters technological elements possessing similar rates of change to avoid costly redesign activities when individual technologies evolve. In this work, we reexamine the theoretical foundations of this method to better understand the nature and over-time dynamics of technologies to support future efforts to design sound techniques for identifying and generating technologically feasible, multigenerational product or product family variants. Such a system will be used to guide the integration of existing technologies and eventually help designers identify, describe, and plan for the adoption of relevant future technologies (those likely to reach technical or commercial maturity during the product line's lifetime). For example, an over-

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[1] From: Ciavola, B. T. and J. K. Gershenson (2012). "Affordances in Technology Modeling." ASME 2012 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, Chicago, Illinois. See Appendix A for a copy of the copyright transfer agreement.

time technology-aware approach to vehicle design might account presently for gasoline, diesel, hybrid electric, and all electric powertrain architectures, and help prepare the way for fuel cells.

Like many design synthesis techniques, the PPIM is based on decompositions of existing artifacts and designs into their functions and components. The allure of these approaches lies in how well they lend themselves to the generation of formal models that can be used for examination of system dynamics and algorithmic manipulation of system architectures. For example, the particular approach used in the PPIM makes use of straightforward matrix-based graph or network representations whose nodes and edges are drawn from a standard set of function, flow, and component primitives. The purpose of this kind of standardization is to attempt to identify a minimum set of abstract object, property, and relationships types that are needed to describe the manner in which a physical artifact or system operates, such that novel ones can be designed to augment, replace, appropriate, compete or otherwise coexist with the original or its elements. However, researchers have recently argued that “there is no underlying theory as to why we ought to consider function as the most fundamental aspect of engineering design,” stating “there is no theory to guide us to the proper use of function in design, what its limitations are, and what underlying assumptions might be.” (Maier and Fadel, 2009) Other researchers have noted that from a practical perspective it is difficult to describe certain types of systems using the type of function model found in the PPIM (Maier and Fadel, 2009a; Schultz *et al.*, 2010).

Maier and Fadel in particular have explored the adoption of the affordance theory of Gibson (1979) in the field of ecological and perceptual psychology, suggesting that it describes a more fundamental aspect of design than theories of function. The laboratory work of Gibson and other researchers empirically grounds key elements of affordance theory.

In this chapter, we will explore the adaptation of the PPIM into an affordance-based system, arguing that affordance theory can improve the function-based technology definition. We will first present the PPIM itself, followed by a preliminary attempt at engagement and integration with the work of Heidegger (1962), in whose writings we find a theoretical framework which anticipated affordances and perhaps even influenced their development. We will attempt to demonstrate how Heidegger's phenomenological investigation of useful things anticipates and parallels Gibson's, resulting compatible, even complementary frameworks.

With this we attempt to map more concretely the relationship between function and affordance, demonstrate utility of affordances for developing arbitrarily granular system decompositions, suggest methods for the identification of technologies and technology architectures, and discuss the current status and future development of our approach.

3.1 THE PLANNED PRODUCT INNOVATION METHOD

The PPIM is a function- and component-based method using design structure matrix (DSM) descriptions for the systematic analysis and representation of technologies used in a product, how they are likely to change, and the type and severity of design risk associated with the change in each technology. It identifies three ways in which technology change can occur in a product, including changes in performance level, principle of operation, and technology architecture.

Beginning the process a physical artifact is chosen for analysis. The artifact is first dissected and analyzed, yielding its function and component structures. The function structure consists of a set of functions and a set of flows which link them, while the component structure consists of a set of components and their linking flows. Functions are mapped to components in a many-to-many bipartite graph using a function-to-component design structure matrix. Functions are directly grouped into technology clusters using function-flow analysis heuristics such as those of Zamirowski and Otto (1999) and Stone. These technology clusters are then annotated with their performance level, principle of operation, and architecture.

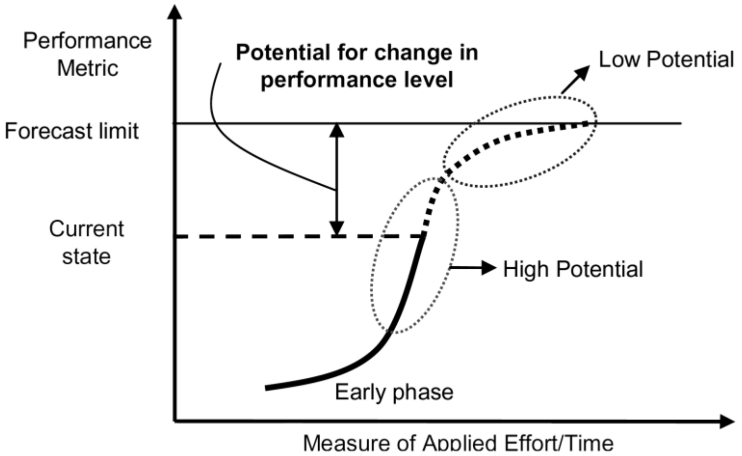

Figure 1: Sigmoid curves for predicting changes in performance level (adapted from Khadke and Gershenson (2008))

Performance level descriptions are quantitative means for evaluating the state of engineering metrics that correspond to the utility of a given technology. The current performance level is mapped to a point on a sigmoid to determine the likelihood of future improvement. Sigmoid curves have been found to model the manner in which technologies increase in performance, with new technologies progressing slowly at first, improving relatively quickly for a time, and finally reaching maturity as opportunities for improvement are exhausted (Twiss, 1992). Each technology's change likelihood is encoded as 'high' or 'low' based on the percent progression along its sigmoid curve. While this formulation is sufficient for a purely engineering description, it fails to explicitly account for subjectivity, either from the user's point of view or that of other downstream systems.

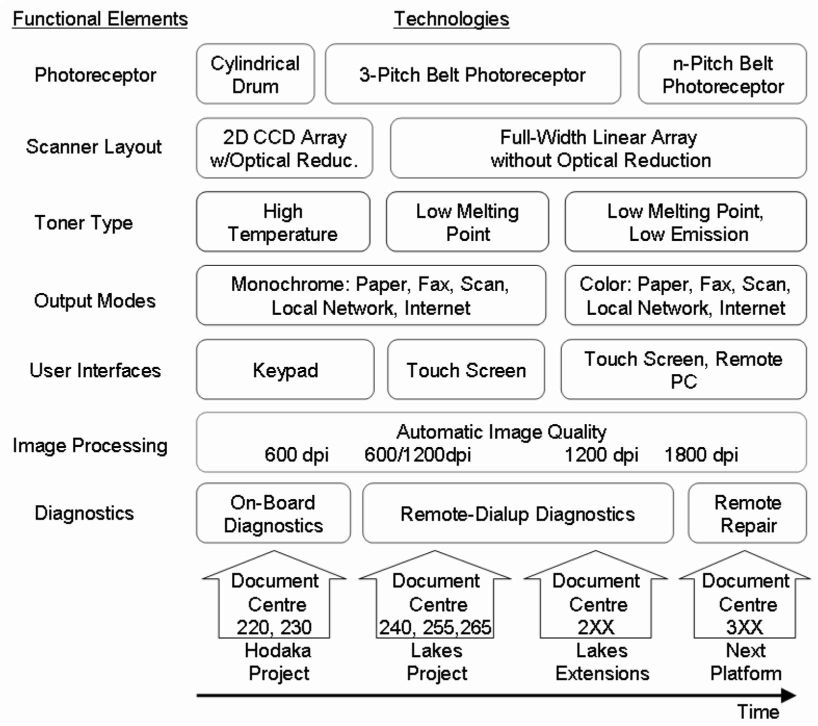

Figure 2: Technology roadmaps (adapted from Khadke and Gershenson (2008))

Principle of operation descriptions are based on technology roadmaps developed by industries to plan the rollout of new operational principles. The change likelihood is assessed as 'high' if there is a new principle on the horizon (Khadke and Gershenson, 2008). However, descriptions of technologies in these roadmaps often vary greatly because there is no consistent, theory-informed approach to differentiating between two technologies: some descriptions are based on performance characteristics, others on behavioral characteristics, and still others based on structural or implementation-based elements. Thus, the notion of principle of operation, despite an origin in expert decompositions, remains *ad-hoc*.

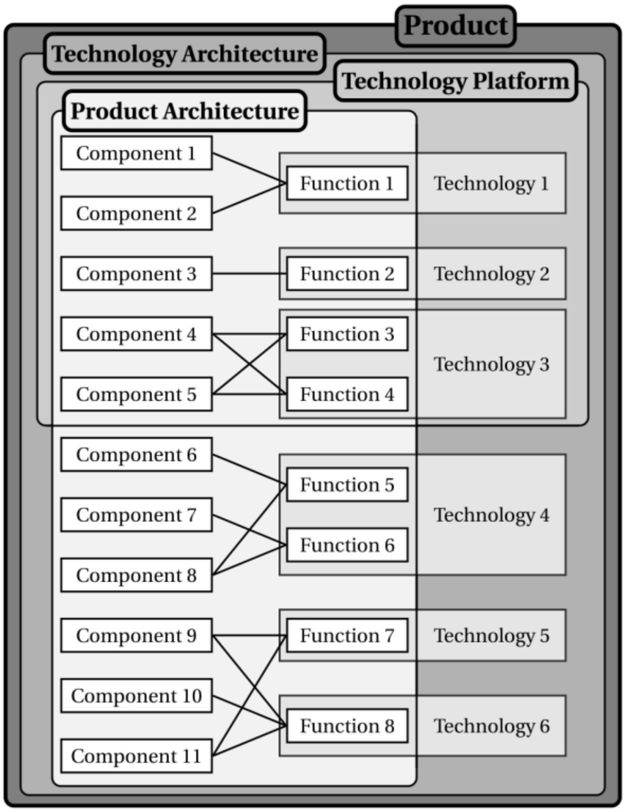

Figure 3: Technology architecture (adapted from (Khadke and Gershenson, 2008))

Technology architecture changes are evaluated based on studies of the evolution of product architecture (Futagami *et al.*, 1993; Balachandra and Friar, 1997). In general, products begin with a modular architecture characterized by strong external dependencies and evolve towards an integral architecture with strong internal dependencies. Architecture measures are derived by mapping functions and their flows to components, and then grouping these components into technology clusters. The set of dependencies which exist between components inside the cluster boundary is then compared to the set of dependencies crossing the outer boundary.

3.2 CLARIFYING THE NATURE OF TECHNOLOGY: INTEGRATING GIBSON AND HEIDEGGER

Two definitions of technology form the basis of the PPIM. In the first, Kroes (2002) argues that "a physical object is a carrier of function, and it is by virtue of its function that the object is a technological object." In the second, Van Wyk (2002) argues that technology is "created competence … expressed in technological entities consisting of devices, procedures, and acquired human skills," which can be characterized according to their function, principle of operation, performance, structure, fit, material, and size. Both of these approaches are functional in nature, and therefore if function is not as fundamental a concept as previously assumed we need a lower level theory. This can be found in Gibson's (1979) concept of affordances and the work of Maier and Fadel (2009a), who propose affordance-based design as a possible fundamental theory of design. Philosophically, we find an alternative theory of technology in Heidegger (1977), built largely on his earlier ontological framework (Heidegger, 1962), and containing distinct parallels with Gibsonian affordance theory (Chemero, 2003; Chemero *et al.*, 2003; Turner, 2005; Dreyfus, 2007).

Both Gibson and Heidegger were concerned with how individuals (organisms and people, respectively) perceive and cope with their surroundings. They each adopt the position that individuals directly perceive irreducible compound features of their surroundings in terms of the benefit or harm they might provide.

Gibson states that from an affordance perspective "to perceive [the compositions and layouts of the environment's surfaces] is to perceive what they afford," wherein "the 'values' and 'meanings' of things can be directly perceived." (Gibson, 1979) He and other researchers have demonstrated through experiments with laboratory animals, infants, and adults that one must learn to perceive these values and meanings through practical experience (Adolph *et al.*, 1993; Klein and Zentall, 2003; Franchak *et al.*, 2010).

Heidegger claimed that for an individual engaged in purposeful action the practical usefulness of something is the most fundamental way it is perceived (as "ready-to-hand"), and its particular usefulness is properly learned and understood only through the act of using it. Differentiating between practical and theoretical modes of relating to the useful item, he states that when using something for a purpose "our concern subordinates itself to the ‘in-order-to’ which is constitutive for the equipment we are employing at the time; the less we just stare at the hammer-Thing, and the more we seize hold of it and use it, the more primordial does our relationship to it become” (Heidegger 1962). This does not preclude the kind of theoretical approach to objects and their properties that occurs in engineering design, but suggests that detached contemplation or examination of the of the object’s physical properties and dispositions is different from and secondary to the experience of using it achieve a goal.

Based on these two perspectives we propose that technology can be understood in terms of affordances. Van Wyk talks of “created competence,” implying the successful use of artificial systems to perform actions that contribute to achieving a goal. In affordance theory, design is the process of “[specifying] an artifact that possesses certain desired affordances to support certain desired behaviors, but [that] does not possess certain undesired affordances to avoid certain undesired behaviors” (Maier and Fadel, 2009). As possible behaviors, affordances depend not only on the properties of the particular artifact but also the user’s ability to realize these behaviors in a way that brings the user closer to their ultimate goal, so long as a proper temporal (Galvao and Sato, 2005) and spatial ordering of behaviors, abilities, and other relationships is achieved. This accounts for both the procedures and human skills in VanWyk’s model.

What remains is function. From an affordance perspective the device and its particular affordances are only one portion of what is necessary for the system as a whole to afford goal achievement. For example, a perfectly functional car is useless without roads both smooth enough to afford rolling and long enough to afford reaching the destination, much like how the well-tuned engine is useless without a fuel supply to afford it chemical energy or a transmission to channel its mechanical power to the wheels. The key difference here between function and affordance is that if in a use scenario an affordance like ‘driveability’ exists, so too must the totality of affordances on which it depends.

Furthermore, each affordance is teleologically subordinate to the ones that depend on it – the afforded behavior is used to realize its dependent affordances (which in Heidegger’s terms are its “in-order-to”), up to and including affording achievement of the user’s ultimate goal. Something like this relationship exists as “purpose” in certain function modeling methodologies like that of Gero (1990; 2004), no guidance is given as to how one can or should map the teleological structure of the system, particularly since purposes are to be identified before functions, before behaviors, and before structures. In some cases there are allowances for reformulating the purpose definitions once a structure is identified, but little guidance as to how this should be done.

3.3 AN AFFORDANCE-BASED PPIM

The type of function model used in the PPIM is based on function decompositions of existing artifacts. These decompositions are twofold, with artifacts decomposed into flow-based models that include a function decomposition and a component decomposition. Examples of such decompositions can be found in the Design Repository (Bohm *et al.*, 2008), in which functions are represented as properties of components (artifacts in their nomenclature). In our case, we are interested in exploring the use of affordances as the fundamental unit of analysis. To do so in the context of the PPIM we require a means of translating between models of function and models of affordance.

Affordances have three roles in design activities: description, explanation, and prescription. (Maier and Fadel, 2009a) In the descriptive mode, affordances are used to capture and codify the structure of designs via derivation from existing systems. In the explanatory mode, affordances can highlight the reason for the inclusion or exclusion of features from a design. In the prescriptive mode, descriptions of a user or artifact's desired affordances can aid designers in the identification of an appropriate set of feasible technological structures (Maier, 2011). Here we will primarily explore the power of the descriptive mode, and seek to understand the degree to which affordances might play a complementary role to functions in design decomposition activities.

A function decomposition generally originates as an attempt to formally describe an existing system to facilitate either its redesign or the design of a different system. The majority of the PPIM's applications have involved existing artifacts in this manner (Khadke and Gershenson, 2008).

Meanwhile, affordances are useful or detrimental behavioral possibilities that exist for an organism (a user) in its environment (use context), given the user's own behavioral abilities and the features of the environment (Chemero, 2003). To analyze an artifact from the affordance perspective can be seen as an attempt to understand the particular possibilities made available to the user via its inclusion in the use context, given the other environmental features and abilities on which these possibilities depend.

The existential dependency of the artifact's affordances on the abilities of the user and features of the user's environment mean that an affordance perspective is naturally suited for the type of analysis of existing and future systems found in the PPIM.

The process of cataloging an existing artifact's affordances begins with the designer perceiving the presence of relevant affordances in a use context due in part to the presence of the artifact. These initial affordances are described by Maier and Fadel (2009b) as those which most directly express the user's needs, desires, or goals, such as 'afford transportation.' These affordances would fall into Maier and Fadel's generic affordance-structure category of "afford desired purposes" - specifically the artifact-user affordance subcategory. However, it is worth emphasizing that the user's highest-level 'goal' affordance may only involve or depend on the artifact itself, such as if the goal is encoded at a higher level, such as 'get from home to work each day.'

Alternatively, one can consider the affordances of only a subsystem, such as a vehicle's transmission. To understand the affordance structure of the transmission relative to the higher-level goal, one must reason backwards from the primary goal, identifying the chain of affordances (and affording entities) used to achieve it. The goal of this process is to develop a structured understanding of the preconditions for realizing a particular affordance in a particular situation. As Norman (2002) notes, "physical limits constrain possible operations," and in each case there are a very large number of supporting affordances that must exist before the high-level affordance can ultimately be realized. In this light, what is provided by the transmission in support of the driver's goal are its affordances. The transmission is in turn dependent on the support of upstream affordances, such as the initial provision at the input shaft of the mechanical power it needs to afford power to the driveshaft.

What we discern here is the existence of sequentially dependent affordances, in which each portion of the system must be arranged such that it can be provided with what it needs to be able to provide its dependents with what they need. Heidegger describes this arrangement using a passenger aircraft, stating that it is revealed to the observer as "standing-reserve," affording transportation precisely "inasumuch as it is ordered to insure the possibility of transportation. For this, it must be in its whole structure and in every one of its constituent parts itself on call for duty, *i.e.*, ready for takeoff" (Heidegger, 1977).

Examination of these constituent parts reveals a number of further affordances on which the vehicle's transmission depends in realizing its contribution to the system's operation. It requires the selection and successful engagement of an appropriate gear ratio for the current operating regime, sufficient lubrication to avoid seizure, reaction torque to prevent its casing from spinning along with its input and output shafts, and so on. This suggests chains of affordance dependencies that branch when an artifact's afforded outputs depend on the provision of multiple inputs or supporting behavioral possibilities.

The question is then: which affordances must or should be described? If one were to take the limiting view of an artifact as a single whole, it can be analyzed at a variety of spatial and temporal scales (Gibson, 1979). Affordances exist and can be described at each of these scales – from the atomic to the planetary – and he suggests that none of these scales are *a priori* more correct than any other, only more useful for the given analytical task at hand. In the PPIM the choice of analytical scale is implicit in the granularity of the component breakdown, as it is in the affordance structures of Maier and Fadel. If we take a preexisting component-level decomposition and analyze it in a use-context we can describe the affordance relationships between these components.

Some of these affordance relationships are partially described by the flows found in function-flow models. If it is known that sufficient mechanical energy flows from a vehicle's engine into its transmission, then it is known that the engine affords mechanical energy to the transmission – but only so long as it is afforded those things it needs for its own operation. From this perspective, with affordances as our fundamental unit of analysis, we can understand functions in the traditional sense as black box descriptions of the roles objects, processes, or systems can play in the use of certain affordances for the creation or modification of other affordances. In such a model they are composite entities, derived from and defined in terms of affordances. As such, they owe their existence to the affordance relationships of their parent system, and the existence of those affordance relationships depend on everything necessary for their achievement. If the engine's function is to convert chemical energy into mechanical energy, we know this determination is valid because we can provide the engine with its necessary inputs (fuel, spark, air, *etc.*) and see that it provides a vehicle or perhaps a dynamometer with mechanical energy. We also find that when it is not afforded a critical element (fuel) it will not provide either system with mechanical energy. It affords mechanical energy because its environment affords it what it needs to do so, and this ability to provide mechanical energy in turn affords transportation to the driver only inasmuch as the driver's abilities, the rest of the vehicle, and the particular driving environment make it possible to actually get to the destination.

Of course, we still have yet to identify a means for specifying technologies or technology clusters. However, doing so in this model is again a relatively straightforward task given our component-based decomposition, particularly since we can account for and represent the functional information used for this purpose in the PPIM. In fact, we find that once we have specified a physically coherent affordance structure that includes at least the flows found in the equivalent function model it is a simple step to specify technologies in a nearly identical fashion to the original PPIM, since in this approach functions are dependency relationships between affordances.

Functions modeled in such a way are linked explicitly to features of the artifact or environment, requiring only that the existence of the downstream affordance depends on the realization of its upstream counterpart. When used to describe flows of material, energy, or signal, affordance-based functions are anchored at the ports or interfaces crossed by the flow, in keeping with traditional approach used in the PPIM.

With this integration of affordance and function it becomes possible to start with an analysis of artifact-user affordances, and by identifying components and cataloging the flows afforded to and by each derive a function-flow model that is compatible with the modularity heuristics used in the PPIM to identify technology clusters.

It is therefore possible to identify PPIM-style technologies using a fundamentally affordance-based approach to system decomposition. Starting from an analysis of artifact-user affordances, the artifact's internal artifact-artifact affordances are identified. Affordances involving the flow of material, energy, or information into and out of each component are then examined for dependence on other of their upstream parent-component's flow relationships. If a dependency exists between one or more of a component's upstream affordances (those things that it is afforded) and one of its downstream affordances (something it affords) then a function can be ascribed to the component. Once a satisfactory level of granularity is achieved, the module identification heuristics the PPIM uses for technology clustering will be applied, and the artifact's technology architecture evaluated.

In this section we attempted to demonstrate a manner in which affordances can be integrated into technology models by demonstrating the manner in which functions owe their existence to affordances. We discussed the identification of affordances, the way in which the existence of a flow affordance can be dependent on its upstream parent's upstream affordances, how an affordance can depend on multiple upstream affordances, and how functions can be mapped to or derived from an artifact's affordance decompositions. In the next section we will explore the ways affordance theory can enrich the PPIM's model of technology state before concluding with a brief discussion of this approach's ramifications for over-time modular and product family design.

3.4 AN AFFORDANCE INTERPRETATION OF TECHNOLOGY STATE

Once technology clusters are identified they are annotated with descriptions of their current performance level, principle of operation, and architecture. We will explore how each of these can be interpreted in and informed by affordance theory.

Performance level measures in the PPIM consist of engineering metrics that correspond to those aspects of the system that drive technology change (Khadke and Gershenson, 2008). The notion of performance can be decomposed and clarified in affordance theory through the principles of complementarity, imperfection, polarity, multiplicity, and quality.

Complementarity is the foundation of such analysis, highlighting the relative nature of performance and implying quality must be evaluated from the perspective of the affordee. Complementarity is a first principle, from which the subsequent four are derived.

Complementarity implies that affordances are necessarily imperfect, particularly in the case of an artifact-user affordance, due to the subjective nature of perception. Dorst and Overveld (2009) observe that "design should not be optimized with respect to objective quality indicators: it should attempt to maximize the perceived representatives of such quantities." However, despite their wording, the subjectivity of perception suggests optimization cannot be performed; there is no such thing as an objective measure of user satisfaction. We must make do with approximations and identification of "room for improvement" (Maier, 2011). As far as artifact-artifact affordances are concerned, the final determination of goodness will be performed by a user, and the principle of imperfection holds. This can be seen in the vehicle example, since the engine's affording of torque to the driveshaft is only judged as 'good' or 'bad' based on the driver's perception of acceleration (or lack thereof). Three factors are at work here – subjectivity, context-dependency, and the mediation of artifact-artifact affordance perception by the rest of the system. Each is in need of further research.

The principle of polarity recognizes that affordances can be "for good or ill" (Gibson, 1979). Considering the example of hybrid vehicles, it is clear that attempting to reduce harmful affordances (*e.g.,* fuel consumption and greenhouse gas emissions) drives technology change in a 'less is better' fashion.

The principle of multiplicity holds that every artifact has multiple affordances, which in our case suggests multiple change-driving affordances exist for any given technology.

Lastly, we have the notion of quality, which refers to "how well the object affords that specific use or behavior." This concept is particularly close to our original notion of performance metrics, though we are reminded that we must mathematically make do with approximations given the imperfection principle.

Principle of operation descriptions in the PPIM are culled from qualitative expert descriptions found in technology roadmaps (Khadke and Gershenson, 2007). Different principles of operation are mutually exclusive and compared using their performance metrics. If we take a principle of operation to be an entity in its own right, there is some difficulty in identifying an objective framework for delineating what counts as such. Clearly, it has to do with the behavioral nature of the system, and like has to do with those behaviors that fundamentally distinguish it from competing technologies. For example, the principle of operation of an internal combustion engine would likely be identified as just that – combustion inside the piston-cylinder system – whether it's Otto's spark-ignited design or Diesel's compression-ignition version. Yet this spark- vs. compression-ignition dichotomy itself makes clear that combustion isn't the only principle of operation up for consideration. Therefore, each technology can have multiple, mutually compatible principles of operation depending on our analytical perspective and level of abstraction.

Can affordances clarify this matter? If we consider the engine as a unit, specifying only its interfaces, it is clear that principle of operation is primarily a property of its internal behavior. By fully decomposing the engine into its component parts, examining its operation, and cataloging its internal affordances, we can identify in the "how" of particular affordances a way to distinguish each technology from the other. Starting with the principle of internal combustion, in both cases the fuel-air mixture affords pressure to the reciprocating mechanism based on the principle of exothermic chemical decomposition. Without this principle, the engine would not function. As for the differing operational principles, the fuel-air mixture in the Otto cycle is afforded its ignition energy by the spark plugs, while in the Diesel cycle the ignition energy is afforded primarily through isentropic compression of the fuel-air mix in the piston-cylinder system. These mechanisms are certainly idealizations which ignore real-world conditions for the sake of analysis - we know for example that compression occurs diabatically in engines in the real world. Still, it is clear that by examining the internal behavior of bounded subsystems in terms of affordances we can identify interactions that depend on physical principles, are fundamental to the operation of the system, and allow us to distinguish between technologies. It is also possible to see how the performance level of these affordances can be used to compare technologies with alternative principles of operation. Further work is necessary to determine how these might best be put to use.

Architecture measures are already largely compatible with affordance theory's component-based decompositions, since the final measures are of dependency relationships within and between groups of related components. These dependencies are affordances, and, as demonstrated in the previous section, can be used to derive the function models the PPIM requires for technology identification.

The other main contribution of affordance theory to technology architecture comes from the principle of polarity; where function theory focuses only on intended behaviors, polarity requires a complete affordance model account for unintended and undesired possible behaviors. This suggests to some that affordance models might need to describe an infinity of afforded behaviors (Brown and Blessing, 2005). However, we can reduce this set down to those interactions which reliably occur at the interfaces between components. Moreover, much like with our description of the compression stroke of the combustion engine as adiabatic, simplifications are both possible and necessary in practice, with the traditional, benefit-oriented function model merely representing the limiting case in which only positive intended affordances are captured. The point is not to fully specify every possible good or bad interaction so much as to provide means and guidance for the description mapping of a broader set of relevant interactions and behavioral possibilities than found function models, such as the dissipation of heat in an electric motor as discussed by Maier and Fadel (2009).

3.5 IMPLICATIONS AND FUTURE WORK

In short, the goals of this research program are a deeper understanding of technology's mechanisms of change over time, identification of opportunities to improve our formal models, and finally the development of tools to aid the design of technologically robust products and product families. In this chapter we identify affordance theory as a prime candidate for achieving these goals, and demonstrated how the fundamentally user-centric approach advocated by affordance theorists might be extended and made at least partially compatible with an existing, device-centric function approach. While this allowed us to augment our descriptions of performance level, principle of operation, and technology architecture, we have stopped short of a detailed analysis of over-time and product family design.

Any useful account of technology change must address the over-time nature of technological evolution. While functions are often modeled as timeless, acausal abstract objects (Galle, 2009), affordances are concrete, world-state dependent behavioral possibilities. By exploiting either one or a series of affordances in the appropriate order over a period of time, abilities and environmental features are revealed or changed, which alters the set of available affordances. Gibson stated that humans alter their environment to change its affordances. It is clear that doing so successfully requires the proper use of the environment's existing affordances, and this path-dependent evolution is strongly recalls the intertwined spatial and temporal dynamics of technology change. An affordance perspective provides a fundamental perspective both of how changes in other technologies might influence the evolution a design and how improving this technology might reveal useful new possibilities or influence the technological evolution of other systems that depend on it.

The PPIM was developed for the identification of technologically robust product and product family architectures, and for their realization using modular design theory. The inclusion of affordance theory in this method will require an examination of the circumstances and degree to which a system's affordances can be influenced through the creation or alteration of product modules. Market segmentation techniques are strongly linked with product family design, and will benefit from the additional analytical tools provided by affordance theory. For example, Chemero's (2003) identification of affordances as arising from possible interactions between features and abilities suggests possible user populations be examined not only in terms of their desires, but also in terms of the features of their use-environments and the abilities they can, should, or must possess.

Lastly, we acknowledge the preliminary nature of this work, and believe there is much fertile soil for both the theoretical development and practical application of affordance theory. Our identification of Heidegger's understanding of technology as complementary to affordance theory is likewise preliminary and requires further delineation of its particular applications and limits. In particular, Heidegger presents an analytical method and ontological framework that is quite different in nature and purpose from that found in function theory. Our focus in this chapter has been on demonstrating affordance theory's compatibility with a particular flavor of function-flow analysis. If the Heideggerian and affordance-based approach is more fundamental in the way we have attempted to demonstrate, then it should be possible to perform a similar analysis with more general theories of function.

3.6 CONCLUSION

In this chapter we sought to incorporate the concept of affordances into previous work on describing technology and technology innovation. These descriptions allow for a more complete understanding of how the design of a system, including its performance level, principle of operation, and architecture. Incorporating affordances into this description results in a more complete picture of a system's possible uses, how putting it to use can help further its user's goals, and how we might differentiate between one technology and another with some degree of rigor.

In the past ten years there have been tireless and steadfast efforts to demonstrate the powerful role affordances might play in design theory and representation. In this work we attempted to bridge one more conceptual and philosophical gap between affordance and function, seeking a means for their integration with the technology model of the Planned Product Innovation Method. Our key contribution here lies in proposing a way in which function can be seen as emerging from the purposeful ordering of affordances "to ensure the possibility of" the user achieving their goals. From this insight we propose a technique for the construction of technology models from affordance decompositions by identifying flows as a basic type of affordance from which functions can be derived. Lastly, we examine a number of affordance attributes in terms of their effect on the PPIM’s descriptions of performance level, principle of operation, and technology architecture. These new attributes extend and clarify the PPIM’s descriptive abilities.

4 THE STRUCTURE OF USER NEEDS

A number of researchers have used affordances to describe, explain, or guide design. Perhaps the most ambitious of the programs is that of Maier and Fadel, in that their work attempts to develop a revolutionary design-theoretic framework. In design theory they see “the existence of unresolved problems that current theories do not solve and phenomena that they do not explain, suggesting an opportunity for a Kuhnian paradigm shift” (Maier and Fadel, 2009a). They examine Simon's (1969) theory of design as an artificial science, the German systematic design of Pahl and Beitz (1996) the decision-based design of Hazelrigg (1998), and Suh's (2001) axiomatic design, identifying two issues with these methods and those like them. First is that beyond being placed inside a larger systematic framework, the methods do not share a theoretical basis. Second is that all methods use the concept of function without providing theoretical justification for its use.

Addressing the first issue is a matter of developing a theory about the nature of design itself – one that can explain the role and efficacy of existing tools, and spur development of new ones. Addressing the second issue requires deconstructing function theory to establish why function is insufficient as a foundational concept, and using this understanding to develop a new model. In this they wish to avoid the problems of function-based approaches – the lack of a theory to guide proper use of function in design, the lack of a theory regarding the limitations of function, and a lack of a theory regarding the assumptions underpinning function theory.

What does it mean to establish a new design-theoretic paradigm, one that unifies and explains existing approaches? For philosophers of design, establishing a paradigm would entail developing a framework to explain and situate design practice, explaining what is designed, why the task of its design is undertaken, and how it comes to be designed. In engineering design, the *what* should explain technological artifacts (functional objects), the *why* should account for the designer's goal in performing the design task, and the *how* should account for the means by which design can be performed.

For engineering design methodologists, establishing a new paradigm would entail developing an ontological framework on which to build design tools. The framework should explain and allow derivation of the phases of the design process and the phases of the product life-cycle, situate design-for-X tools within a unified framework, and provide new opportunities to develop practical tools that better reflect the reality of design practice.

Maier and Fadel (2009a) see an opportunity for both philosophical and methodological shifts through the adoption of the theory of affordances. They address the provision of a common philosophical basis by focusing on the benefits of a *relational* design theory. Relational properties have played a role in other design philosophies and methodologies (*e.g.*, Domain Theory (Andreasen, 1980; Andreasen, 2011)), but none have used relations as the central element from which all others are derived. Maier and Fadel use ecological psychology's affordance theory (as opposed to function theory) as their foundational analytical framework because affordances are real, observer-independent relational properties.

In this approach, the process of design is the "specification of a system structure that does possess certain desired affordances to support certain desired behaviors, but does not possess certain undesired affordances to avoid certain undesired behaviors" (Maier and Fadel, 2009a). This model is based on the idea of a core Designer-User-Artifact (DAU) system situated in an environment populated by entities such as the law, parent companies, the natural environment, manufacturers, and the economy. Interactions between the entities in the DAU system are described in terms of information transmission. Users provide designers with the "information needed to specify which affordances should and should not exist in the artifact under design." Designers develop "specifications of the artifact's properties that determine its various affordances internally (*i.e.*, AAA) and externally (*i.e.*, AUA) to the targeted users." Users interact with artifacts by way of the artifact's AUAs. Affordance-based tools for clean-sheet (innovative) design, redesign, and reverse engineering use matrix-based descriptions of the behavioral possibilities each system in the user's environment must provide or prevent relative to the user or other systems in the user's environment (Maier and Fadel, 2009b).

4.1 A STEP FORWARD

Maier and Fadel present a compelling argument for affordance-based design along with descriptions of several methods for designing affordances. However, they stop short of analyzing the fundamental structure of affordance relationships and the implications of that structure for the design process. Brown and Blessing (2005) critically evaluate Maier and Fadel's approach and suggest that function- and affordance-based methods complement each other, though little reconciliation work has been done. Instead, there has been parallel development of affordance and function theory, with only minor attempts having been made to integrate the two concepts.

It is our opinion that the primary obstacle to the adoption of affordances in the engineering community is a lack of concrete methods for understanding affordance relationships and a shortage of clear roles for affordances to play. As it stands, it can be difficult to see the benefit of affordance-based methods, especially when one is familiar with function-based approaches. As currently discussed in the engineering design literature, affordances can be "just about anything" (Maier and Fadel, 2006), and limited work has gone into exploring the proper role of affordance representation and reasoning in the design process.

The goal of this chapter is to use the lessons of function-based design research to explore practical representational opportunities provided by affordance theory. In section 4.2, we discuss the role and limitations of function in design, and suggest how affordances might systematically bolster function-based design's representational power, particularly in early-stage design. In section 4.3 we present definitions of function and affordance, and make the case for more fully adopting the language and perspective of affordance theory's parent field of ecological psychology. Section 4.4 uses the tools of ecological psychology to reexamine the nature of affordance-based reasoning in design before suggesting a manner in which its proper role might be justifiably expanded. Given this finding, section 4.5 presents a representational hierarchy for use-centric design processes with affordance-based design reasoning. Section 4.6 presents our conclusions and suggestions for future work.

4.2 RECONCILING FUNCTION AND AFFORDANCE

Function is a foundational concept of engineering design, and was used by Maier and Fadel (2009a) as a foil for affordance. Function is considered one of the most fundamental aspects of artifact nature (Kroes, 2009), and most commonly taught design processes focus on the development of functional technical artifacts using function-based tools. Engineering education and best practices have seen a rise in the use of design-for-X toolkits and design-thinking methods that seek to address blind spots in function-based tools (Andreasen, 2011).

Function models are used to translate from human intention to artifact structure without over constraining the solution-space, but are limited in their ability to do so. A full specification of a system using a function-based approach requires a large amount of supporting intentional and physical information, and even if this information is supplied the model is only capable of describing the proper, intended way the device is to be used. Function theory does not provide designers with tools for understanding or designing around situations that do not fit the model of proper use, or situations which occur before or after the use-phase of the life-cycle, or (for Pahl and Beitz-style (Pahl and Beitz, 1996) function-flow models) situations in which there is no transformation of operands, necessitating the use of design-for-X. The most common function-based design approaches provide limited support for capturing the role of users, other artifacts, and environmental features in the use process.

Function theorists have developed extended modeling frameworks to address the gaps in function-based approaches (Chandrasekaran and Josephson, 2000; Gero and Kannengiesser, 2004; Brown and Blessing, 2005; Vermaas and Dorst, 2007; Galle, 2009). Based on meta-analysis of these approaches, Vermaas (2009) suggests that a full specification of a system includes both intentional and physical information, and can be expressed in terms of goals, actions, functions, behaviors, and physical structures (Figure 4). This model is intended to highlight the importance of not only specifying the properties of the device itself, but also intentional and physical information regarding its use (Vermaas and Garbacz, 2009)

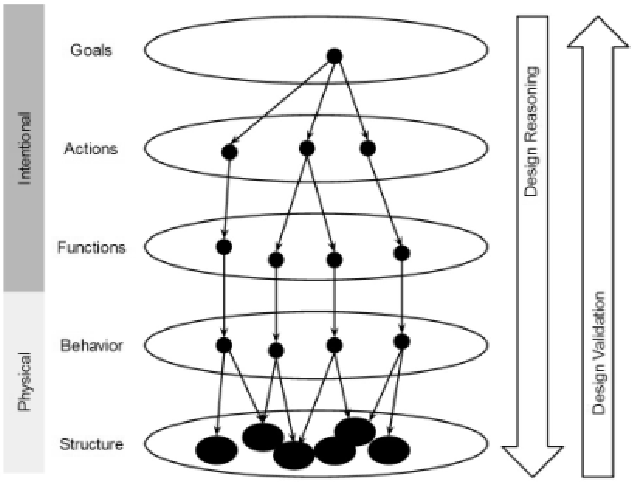

Figure 4: Modeling artifact use requires capturing five levels of intentional and physical information (Adapted from (Vermaas, 2009))

Maier and Fadel (2009a) contend that affordance-based techniques offer a philosophically and scientifically rigorous foundation for design theories and design processes that obviate the need for ontological and methodological patchwork. While functions are a foundational concept for mapping designer intentions to artifact behaviors, we argue that affordances provide a foundational concept that can underlie representations at each level, bridging each of the gaps between goals, actions, functions, behaviors, and structure across the product life-cycle.

4.3 AFFORDANCES IN A FUNCTIONAL WORLD

Functions and affordances are both ways to convey *behaviors*. Functions are intended behaviors, described either in terms of what a device itself does or in terms of the external effects that the device has on its environment. Function modeling provides tools for representing "what the device and its components do or what the purpose of the device and its components are" (Erden *et al.*, 2008). Gibson defined affordances as what the environment offers or provides the organism, either for good or ill (Gibson, 1979), and subsequent work has refined this formulation. Affordance modeling provides tools for representing what it is possible to do in a particular situation. Current research describes affordances both in terms of possible actions (Turvey, 1992; Michaels, 2003; Pols, 2012) and possible behaviors (Chemero, 2003; Maier and Fadel, 2009a; Gero and Kannengiesser, 2012. Defining affordances as possible actions is useful for investigating the process of practical goal achievement, since actions are intentional, goal-directed behaviors {Michaels, 2003 #463). Defining affordances in broader terms as possible behaviors is useful for investigating and designing unintended or undesired behaviors, as in Maier and Fadel (2009a).

The shift from function to affordance entails more than just a move from intention to possibility. As the foundational concept of the field of ecological psychology, affordances are part of a rich ontology for describing how animals are able to successfully interpret and act in their environments (Shaw *et al.*, 1982). These descriptions occur at the "ecological level" (Gibson, 1979), which means that they are developed relative to an organism and are defined at a level that is perceptible and behaviorally meaningful to that animal. There are roughly five elements of the ontology of ecological psychology that we require for our discussion of affordances - *organisms*, the *environment*, *objects*, *abilities,* and *situations*.

Organisms are the living entities (microorganisms, animals, people) that perceive and use their environments' affordances according to their individual needs and abilities. In function-based design the relevant organism – the one whose needs are to be addressed by the artifact's functionality – is usually called the *user*, but affordance-based design suggests that the term *user* can and should also be applied to those participating in other phases of the design's life-cycle (Maier and Fadel, 2009a; Cormier *et al.*, 2013). For example, in the design phase, the organisms can be designers, engineers, focus group participants, and/or beta testers; in manufacturing they are workers, managers, industrial engineers, and/or inspectors; and in end-use they are traditional users, service technicians, and/or retailers. Throughout the rest of this chapter, we will use the term *user* interchangeably with *organism* to mean a person pursuing their goals by interacting with their environment.

The *environment* is the terrestrial arena in which organisms go about their lives, including the medium in which they move (air or water), the terrain and its features, other organisms, and objects including (but not limited to) artifacts and other manmade systems. Affordances arise from behavioral compatibility between organisms and portions of their environment, and therefore environmental features are defined at what Gibson calls the "ecological level," which is only concerned with "the habitat of animals and men, because we all behave with respect to things we can look at and feel, or smell and taste, and events we can listen to" (Gibson, 1979). Ecological descriptions of an organism's environment focus on the set of available affordances (Shaw *et al.*, 1982) and the information available for their perception (Gibson, 1979). The physical environment that underpins the descriptions of ecological psychology is similar to the environment of function-based design, but it is defined relative to a given organism rather than relative to a device (*e.g.*, as with the notion of environment-centric functions (Chandrasekaran and Josephson, 2000)).

Objects are "the furniture of the earth," and can be either attached or detached to the earth or to other objects (Gibson, 1979). Attached objects are rigidly affixed to other objects (as assemblies in cars) or to the earth (as a building's stairs). In general, objects must be comparable in size to the organism to afford useful behaviors (*e.g.,* a fist-sized rock can be thrown as a weapon, while a boulder or a pebble cannot), and often the primary target of design activities. Designed/manufactured/useful objects are called artifacts (Houkes and Vermaas, 2010) or devices (Brown and Blessing, 2005). Objects – and artifacts in particular –

can have both affordances and functions. An object's affordances are the totality of behaviors the user can perform with it, and an object's functions are (generally) the those behaviors it is intended to perform or for which it is used (Houkes and Vermaas, 2010). An object's functions may make it useful as a tool, in which the object provides its user access to new affordances that allow the achievement of new goals. When used as tools, artifacts and other objects shift the user's perceived organism-environment boundary. "When in use, a tool is a sort of extension of the hand, almost an attachment to it or a part of the user's own body, and thus is no longer a part of the environment of the user … the boundary between the animal and environment is not fixed at the surface of the skin but can shift" (Gibson, 1979). For example, when a person is in possession of a hammer (or an equivalent tool for storing and releasing kinetic energy), nails and wood afford building; when not in possession of a hammer, carpentry is impossible. In many cases (especially with simple tools) users can intuitively perceive the uses objects afford, and much of the affordance-based design literature focuses on how designers can facilitate the affordance perception process during design (Norman, 1990).

Abilities (also called *effectivities*) are the complement of affordances (Shaw *et al.*, 1995). Where affordances are the action opportunities that the environment presents an organism, abilities are the behavioral means for acting. The ability-affordance dualism guides designers to approach the design of particular affordances based on an understanding of what abilities the user has in a situation, and serves as a means to partition the organism-environment system in terms of behavioral preconditions for action. Artifact functions may augment or extend-user abilities and allow users to take advantage of artifact-use-dependent opportunities in their environment. For example, a push wheelchair extends a person's ability to transmit power with their hands, affording the ability to navigate portions of their environment that would be otherwise inaccessible.

Situations (or *occasions*) are instances in which particular relationships exist between organisms, the environment, and the objects in the environment (Turvey, 1992). These relationships are both intentional (*e.g.*, an organism can be focused on a specific goal or be in the process of performing an action) and physical (*e.g.*, the organisms and objects may be undergoing behavioral interactions, or may have a specific spatial configuration – mode of deployment in the functional language of Chandrasekaran and Josephson (2000)). In this way, a situation description can capture information about a previous, existing, expected, intended, or desired state of affairs. Physically, situations can be described in terms of particular users, their environment, its objects, and their configuration. Ecologically, situations are sets of affordances (Shaw *et al.*, 1982), which exist if "relevant compatibilities" hold between the organism and its environment. A behavior is afforded if there is ecological compatibility between an organism and its environment (Gibson, 1979); if the means for acting and opportunity for action coincide. Maier and Fadel (2009a) extend the concept of ecological fit to interactions between components, artifacts, and other inanimate elements of the organism's environment.

Shaw *et al.* (1995) show that people learn to directly perceive the artifact-dependent affordances of their environment relative to their artifact-dependent abilities. This finding implies that the design and analysis of functional objects should include a coherent account of the relationship between abilities, functions, and affordances. However, affordance- and function-based design makes use of different types of reasoning processes. In the following section, we discuss these reasoning processes and show how the ontological tools of ecological psychology can reconcile the approaches.

4.4 REASONING WITH AFFORDANCES

Brown and Blessing (2005) understand the difference between function- and affordance-based design reasoning as "given a function predict possible devices," versus "given a device predict possible user actions." We see the reasoning processes for function- and affordance-based design perspectives as applying in both directions. From the function perspective, devices are designed to perform particular intended behaviors, and designers are thought to reason from functions to behaviors to device structures (Gero and Kannengiesser, 2004) and to recognize functional behaviors in structures (Chandrasekaran and Josephson, 2000; Houkes and Vermaas, 2010). Meanwhile, affordances are form-dependent behavioral possibilities that cannot be fully specified until the structure of the device has been designed. Brown and Blessing's formulation thereby questions the validity of an affordance-based design theory by identifying a chicken-and-egg problem: without a device, how can one identify its affordances?

Specifying an affordance requires an "irreducible minimum of three logical terms" that include an organism action term (the behavior that may be performed), the physical layout of the "surfaces and substances" of the environment (the resources with which to perform the behavior), and relevant compatibility relationships between the organism and environment (the conditions under which an organism can in fact perform the behavior in this environment) (Shaw *et al.*, 1982). Brown and Blessing's chicken-and-egg problem arises from the fact that the layout and compatibility terms are necessarily incomplete in the early phases of a design process. This is compatible with affordance-based design processes, and serves to clarify the affordance-based reasoning process.

In the early, problem-definition stages of affordance-based design, designers are seeking to understand which affordances each situation must present to which users and why (Maier and Fadel, 2009a). This affordance-based identification of user needs is not necessarily an identification of fully specified affordances, which would require knowledge of the design to complete the description of the physical layout of the environment and the environment-organism compatibility conditions. Instead, we argue that early-stage affordance descriptions are necessarily incomplete, perhaps containing only Shaw's organism action term and incomplete information about the surfaces and substances of the environment. In this approach, early affordance-based design reasoning is no longer about predicting possible actions given a device, but instead about identifying desirable (or undesirable) actions or behaviors. These may currently be possible (driving a car to work) or impossible (as was putting a man safely on the moon in 1960) given the lack of a device-to-be-designed, but any successful design should allow performance of a desired action or behavior, or suppress those that are undesirable.

However, understanding and designing the set of actions, environmental features (including artifacts), and compatibility conditions for the successful execution of possibly complex actions (like walking on the moon, or driving to work) is nontrivial and benefits from a structured approach. In function-based design, high level functions are often too broad for designers to immediately identify working principles or embodiments capable of realizing them, and rely on decomposition processes to break down overall functions into manageable, directly realizable subfunctions (Pahl and Beitz, 1996). While it is true that affordances are form-dependent, there is evidence to believe that, as with functions, it is possible to reason directly from a sufficiently well-formed statement of desired affordances directly to working principles or even embodiments (Maier, 2011). After defining desired affordances, designers are encouraged to use any appropriate ideation tool, such as brainstorming, TRIZ, or IDEO's Deep Dive (Maier and Fadel, 2009b). Since even a simple action involving an artifact may refer to both artifact manipulations and any number of intended effects, a desired action opportunity may be described in terms of behavioral effects, thereby allowing designers to apply the tools of traditional function-based design processes.

In this section we have shown that designers in the early stages of an affordance-based design process can be understood as reasoning first about currently existent or nonexistent affordances based on the current situation (*e.g.*, existing or well understood users, objects, environmental features, and user situations). The life-cycle processes of design, manufacturing, and distribution are collectively performed to enable these affordances (*e.g.*, by designing, manufacturing, and selling a new car that will afford driving to work), and it is the role of designers to plan the process of affordance creation. In the following section, we present a framework for capturing affordance related information in a structured fashion. This framework is intended to fill roles similar to those of the function decomposition and function-behavior-structure reasoning framework so that designers can systematically identify, define, and decompose affordances during design processes.

4.5 DESCRIBING USE WITH AFFORDANCES

In this section we develop a roadmap for practical affordance-based representational tools. Using the tools of ecological psychology described in section 4.3, we specify the elements of the hierarchy of representations (Figure 5) for descriptions of product use that expand upon typical function-based descriptions.

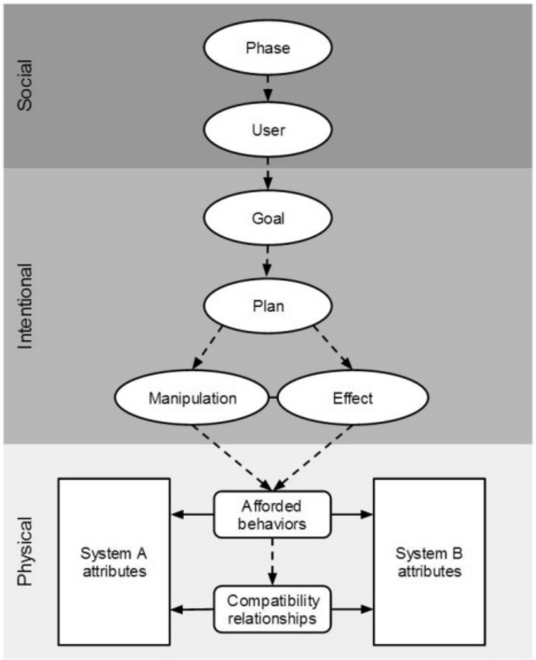

Figure 5: A representational hierarchy for affordance-based design.

Since we wish to capture information from a use perspective, our hierarchy begins by identifying use contexts in terms of life-cycle phases. Phase descriptions are a means for clustering information that pertains to more than one individual, such as shared goals within user groups or organizations, interactions between users[2], and communal resources. Lower level terms (goals, plans, manipulations, and effects) describe the intentions of individual users participating in each life-cycle phase, and provide the action descriptions that underpin the affordance-based design reasoning process. Opportunities for users to achieve goals (*e.g.*, by using an artifact) can be captured by describing a use plan in terms of afforded manipulation and effect opportunities (Pols, 2012). Afforded actions and behaviors can occur between systems under appropriate circumstances. These circumstances are defined in terms of behavioral and physical compatibility relationships between system attributes, including attributes of the user and use environment.

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[2] As mentioned earlier, 'user' can refer to any participant in any life-cycle phase, which includes but is not limited to end-use.

The representation in Figure 5 can be used to reason in two directions: from the top down and from the bottom up. Top down reasoning uses the representational hierarchy to guide the identification of solutions for higher level requirements, similar to reasoning from functions to working principles as in Pahl and Beitz (1996). The goal of bottom up reasoning is either to identify possible uses of existing systems (*e.g.*, Brown and Blessing's (2005) identification of possible actions given a device) or to determine whether a design described at a low level will meet higher level requirements, such as a set of possible actions allowing the achievement of a goal. In the rest of this section we discuss the process of representing each level of the hierarchy, how each level is linked to the levels above and below it, and how information at a particular level can be linked to other representations of the same type.

Life-cycle phases are all treated as use processes in affordance-based design (Maier and Fadel, 2009a). Using phase-level descriptions as the highest level of the hierarchy allows designers to take advantage of user commonality by identifying collective goals and intentions (which Searle (1997) argues are distinct from individual goals and intentions), as well as situations and environmental factors that are similar amongst disparate users participating in similar life-cycle processes. In the design process, this early phase-based breakdown represents the design team's collective understanding of the life-cycle and user types. For example, design, manufacturing, use, and retirement each have users playing different roles with respect to the organization and each other.

Top-down life-cycle design involves identifying design-for-X opportunities early in the design process, thereby minimizing the amount of later redesign. Early, structured identification of constraints from throughout the life-cycle allows designers to eliminate or refine design candidates to meet those constraints before committing expensive detail design and manufacturing resources. Bottom-up design involves analyzing known design attributes in terms of their effect on each life-cycle process. For example, Boothroyd and Dewhurst's (1987) rules for minimizing part count are a bottom-up analysis that examines an existing design's physical structure in terms of its assembly processes, thereby helping designers minimize the number of assembly actions each assembly worker performs per product. Designers do this by modifying the physical structure of the product components (*e.g.*, their form, number, and configuration), while retaining the ability of the product to provide the same functional behaviors.

Life-cycle phases can be decomposed into interrelated sub-phases. For example, the manufacturing phase of a complicated system can be roughly broken down into raw material acquisition and preparation, component manufacturing, subsystem assembly, final assembly, integration testing, and packaging, each with different groups of system users. The phase breakdown and user identification may be particular to each organization, design process, and design problem, but the principle of complementarity (Maier and Fadel, 2009a) can guide their identification. Complementarity states that affordances involve interactions between ecologically compatible systems. In the context of use-phases at the high level, complementarity occurs at an interface where one group of users collectively has a goal of providing another group of users with the resources the latter need to achieve their own goals. For example, the various employees of a design and manufacturing firm share the goal of providing a useful, desirable product to many end-users. The design department provides manufacturing the information they need to achieve their goals, manufacturing provides the end-user the ability to acquire finished goods, and the user provides recyclers the raw materials they need for their recycling processes. If the upstream users provide faulty information or materials, or if the downstream users are unable to receive the information or use those materials, then there is ecological incompatibility or inefficiency in the organization.

Users are identified and described based on their goals (Maier and Fadel, 2009b) and characteristics of their situations in terms of resources, abilities, or locations in the environment, as well as in terms of social or cultural attributes and relationships that determine the affordances they perceive and the actions they can perform (Gibson, 1979) (Figure 6). Users can be grouped based on these attributes to identify and exploit commonalities and differences in the design process (*e.g.*, in terms of ability or goal orientation). Top-down reasoning identifies users at each life-cycle phase, and guides designers to identify different types of users early in the design process. Bottom-up reasoning identifies users by reasoning about the type of person who would be interested or able to achieve particular goals, the type of person who is a user of an existing system, or the types of people whose involvement is necessary (*e.g.*, because they posses particular resources or abilities) given a design.

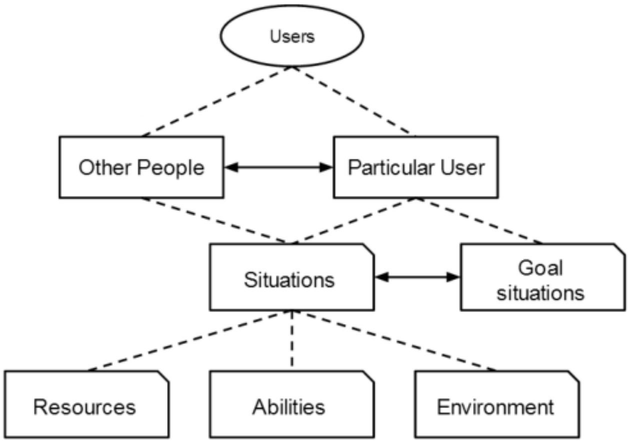

Figure 6: Users are differentiated by their situations, including goals, resources, abilities, and their place in the environment.

User groups are commonly used for segmenting end-user markets, the same principles apply across the life-cycle. Relationships between users or user groups can be described based on what they provide or afford each other. Gibson (1979) states that “the richest and most elaborate affordances of the environment are provided by other animals, and for us, people.” This information is particularly social in origin, with culturally and institutionally defined roles governing user interactions (*e.g.*, between management and labor) and realized through social actions (Pols, 2012) (*e.g.*, hiring) and physical interactions (*e.g.*, working together to lift a heavy component during assembly). Representing inter-user relationships is a tool for analyzing and designing organizational structures (*e.g.*, information passing and decision making within the firm) and individual relationships (*e.g.*, the number and type of users needed to execute a use plan, along with their interactions). User interactions can be sought by identifying situations in which two or more users are participating, and highlighted when the participation of multiple users is necessary to achieve an individual or collective goal. A user's resources are what they have available to use to achieve their goals, including money, objects, artifacts (which can already exist or be those undergoing design), environmental features, and other individuals. Resources are physical things described at the structural and behavioral levels, while abilities are described at the behavioral level in terms of what the user is able to do with their resources.

User type identification (Figure 6) involves segregating particular users of interest from other people who may be involved in a use situation and may even be users themselves, such as manufacturing workers (user) and industrial engineers (others) in a factory environment. Both are involved in the manufacturing process, but the affordances available to and used by each group are different. These differences in affordance availability and use arise from differences in goals, resources, abilities, and environment. Though they work together, a worker may have the goal of performing a manufacturing process, while an industrial engineer has a goal of improving the manufacturing process. The worker's physical resources (entities providing useful affordances) include raw materials, equipment, and coworkers. The engineer's resources include workers, documentation and diagrams, simulations, and relationships with higher levels of management. Abilities describe the actions a user is capable of in a particular situation or type of situation and are a primary design constraint when considering usability. Design for manufacturing and industrial ergonomics are two fields that catalog worker abilities and provide tools allowing industrial and manufacturing engineers the ability to systematically account for these abilities in their product and system designs. The field of universal design seeks design solutions that provide the same affordances regardless of differences in ability.

Goals are users' intended or desired situations, and are achieved by performing actions afforded by earlier situations. As intended situations, goals can be described in physical (both structural and behavioral), ecological, or social terms. Physically, structural descriptions capture a state of affairs in terms of user attributes and configurations of environmental features, objects, artifacts, and organisms, while behavioral descriptions capture it in terms of physical interactions or dispositions. Ecological descriptions are in terms of abilities that the user should possess or action opportunities that the goal situation should afford the user. Social descriptions are cultural, institutional, or interpersonal states of affairs, especially those that determine what social actions the situation affords.

Overall goals (like overall functions) can be realized by achieving subgoals in parallel or in sequence. Representing relationships between initial situations, intermediate subgoals, and overall goals in terms of situations and their variables allows designers to evaluate alternative means of goal achievement and to verify that particular goals are not conflicting. Ecological descriptions of situations (in terms of abilities and affordances) describe what it is possible to do in that situation, and therefore can capture the set of situations (including goals and subgoals) that a user is able to bring about. Goals can be mapped to plans consisting of lists of afforded actions, which allow designers to document, examine, compare, and optimize use processes.

From the top-down, user roles and individual situations allow designers to reason about their likely goals. If actual users already exist or prototypical users can be identified, they can be interviewed or observed to develop goal descriptions. From the bottom-up, known action opportunities can be used to reason about what situations are possible to bring about. Bringing about a new situation results in new affordances, and identifying possible situations in this fashion involves analyzing nested and sequential affordances (Gaver, 1991). Likewise, bottom-up reasoning can identify undesirable situations and affordances that designers may work to suppress.

Plans describe the sets of parallel or sequential actions that should allow users to transform their initial situations into their goal situations by achieving intermediate subgoals. Pols (2012) shows how an opportunity to use an artifact (*e.g.*, to achieve a goal) can be described in action-theoretic terms as a use plan consisting of sets of manipulation and effect opportunities. Plans do not have to be static (*e.g.*, do A then do B) but can be captured in terms of sets of necessary and sufficient action opportunities. For example, it is not necessary to pre-plan each pedal press or turn of the steering wheel to use a car to get to work.

Plans can be described and differentiated at four levels of decreasing importance (Figure 7): in terms of the goals they are intended to accomplish, in terms of the objects used, in terms of the actions performed, and lastly, if necessary, in terms of the action order (Houkes and Vermaas, 2010). From the top-down, plans are first identified based on goals, followed by objects and particular actions. This top-down plan analysis allows designers to systematically consider multiple possible means of goal achievement, and directs them to examine the available structural resources and behavioral abilities to do so. For example, when planning a design project, designers should consider what resources the intended end-user already possesses, and what abilities those resources afford her. This method allows comparisons of competing designs, technologies, and techniques.

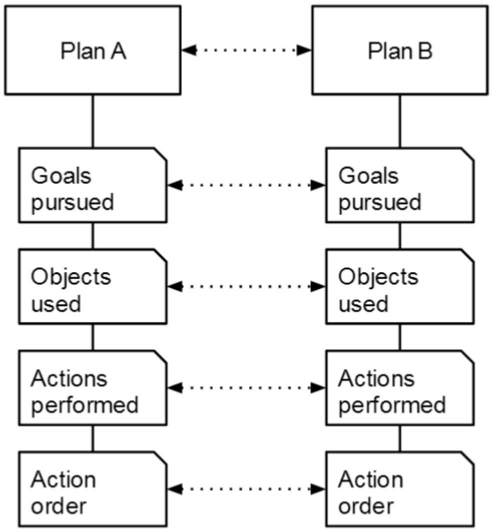

Figure 7: Plans can be compared and differentiated at four levels: goals, objects, actions, and order.

From the bottom-up, plans can be constructed by analyzing what abilities and affordances exist, and selecting and ordering action opportunities in a way that should bring about the goal state. This is roughly the process that planning algorithms perform, and allows object-agnostic plan development. Since planning languages generally do not include preferences beyond costs and constraints, algorithmic, bottom-up planning approaches will select the lowest-cost means to goal achievement. For designers, an algorithmic, bottom-up planning perspective highlights unintended uses and provides a way to describe uses or plan-types that should be designed against (*e.g.*, by designing out negative affordances).

Relationships between plans can be analyzed in terms of user participation, goals achieved, object involvement, and actions performed. Analyzing these relationships allows designers to identify commonality, similarity, dependency, and incompatibility between plans. Relationships based on user participation are identified by first mapping users to plans, if the user executes relevant sub-plans or actions. Plan relationships at the goal level are based on whether the achievement of one goal is a prerequisite for executing a plan for achieving another goal. Object-level relationships were analyzed by Galvao and Sato (2005), who present a Function-Task Interaction Matrix (FTIM) that allows designers to identify which artifact functions are involved in performing which tasks. Lastly, relationships at the action level arise when performing a particular action is a necessary step in the execution of multiple plans. Plan incompatibility may be identified if an action or goal in one plan is incompatible with one or more actions in another plan, either by bringing about a situation in which it is impossible to perform necessary actions or by not allowing actions to be performed concurrently. Identifying alternative means of goal achievement at the goal, object, or action levels can be used to couple or decouple plans (increase or decrease inter-plan dependencies).

Manipulation and effect opportunities are basic affordances at the action level. A basic affordance is an interaction that can be captured at a high level in action terms or a low level in behavior terms, and its representations can include supporting information at the function and structure levels. Manipulation and effect opportunities are designed and analyzed in terms of behaviors and relationships among structural attributes of the systems involved. Manipulation and effect are two ways of describing the same action, such as pressing a computer's power button (manipulation) and causing the machine to turn on (effect). A basic action opportunity like this can include a traditional functional description by linking manipulation behaviors to effect behaviors.

Relationships between manipulation and effect opportunities are the domain of traditional transformation-based functional design methods like that of (Pahl and Beitz, 1996). A manipulation opportunity is identified when a user is able to directly act on an object or system in a way that causes an effect elsewhere in the system. If an artifact provides the ability to cause an effect in this fashion, it represents a functional extension of the user's abilities (Shaw *et al.*, 1995). Some manipulation opportunities (*e.g.*, pressing the brake pedal of a car) contain the possibility of having multiple effects, either simultaneously (*e.g.*, slowing the vehicle and making the brake lights come on) or based on the particular situational context (*e.g.*, slowing the vehicle when in motion versus deactivating the ignition interlock when the car is turned off).

From the top-down, manipulation and effect opportunities are identified based on analysis of plans and the initial or intermediate situations that occur as plans are executed. From the bottom up, manipulation and effect opportunities are identified based on analysis designed based on particular effects or based on the analysis of the user's abilities and the configuration and behavioral dispositions of their environment.

Affordance analysis, as previously discussed in section 4.3, involves a three-fold description of the user action, physical configuration of the environment, and behavioral and structural compatibility relations (Figure 8). Following Shaw (1982), these generic affordance statements take the form *the environment E affords behavior Y to organism O in a situation S in which conditions K are true*. The conditions *K* are captured by statements about behavioral and structural attributes of the environment and organism relative to each other – the *preconditions* for the realization of *Y* by *O* in *S*. In the end, behaviors must be realized through the existence or creation of structural attributes *A*.

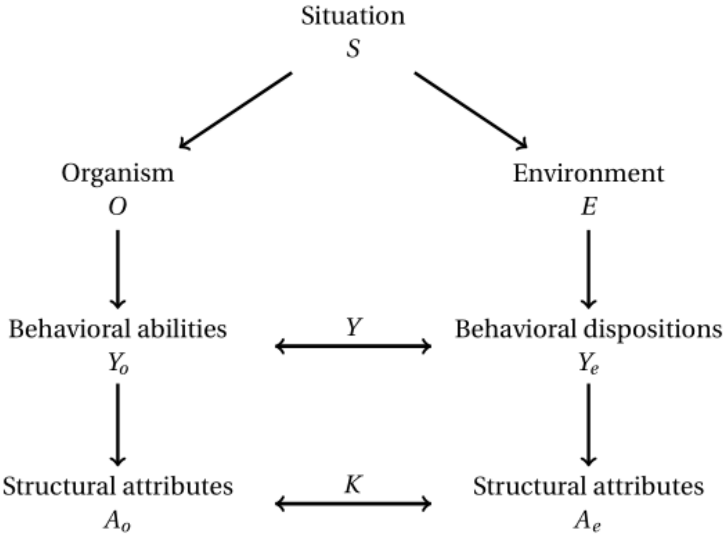

Figure 8: Ecological fit implies complementarity between organism and environment in a situation S.

This complementary relationship can be stated as conditionals and behaviors both in terms of aspects of the environment and its dispositions relative to a type of organism (*e.g.*, in terms of an opportunity for action – an affordance) and in terms of the organism and its abilities relative to a type of the environment (*e.g.*, in terms of an organism's means for acting – its abilities). These two approaches emphasize either the environment's features, attributes, and behavioral dispositions relative to a type of organism, or the organism's resources, attributes, and behavioral abilities relative to the features of its environment.

4.6 CONCLUSIONS

In this chapter, we have sought to continue the development of an affordance-based approach to mechanical design. Building on the paradigm-shift approach of Maier and Fadel (2009a) we identified a set of philosophical and practical requirements that any new paradigm must meet, specifically that the paradigm should account for the nature of the task of design in terms of the nature of the thing being designed and the process of design generation. We identified design ontology as the key enabling tool for paradigm establishment from the perspective of design methodology, and sought to justify the adoption of affordances, affordance-based design, and the ecological perspective. In section 4.1, we discussed the barriers that face the adoption of affordance-based methods by the engineering community, particularly a lack of shared understanding of the conceptual structure of affordance theory and its relationship with traditional function-theoretic approaches. We presented the focus of our efforts on helping to realize the ability of affordance theory to provide a more complete ontological and representational framework for design processes. Building on existing work in the field of function theory, we sought to develop such a representational framework by building on Vermaas and Garbacz's (2009) dual intentional/physical model of descriptions of device use. With a use-centric approach already a fundamental aspect of affordance-based design, we presented an affordance-based representational hierarchy in section 4.2 that situates affordance and function knowledge in a common action-theoretic framework. In section 4.3 we present neglected elements of the affordance ontology of ecological psychology, and demonstrate their relevance to design theory and the establishment of a structured approach to affordance-based reasoning. We discuss the structured use of the terms *organism, environment*, *object*, *ability,* and *situation* to capture affordance relationships. Using this language, section 4.4 elaborated on our understanding of the analytical and representational opportunities provided by an affordance-based account of device use. In section 4.5, we then discussed how each level of our hierarchy can be modeled from the top down, from the bottom up, and how relationships between elements on the same level can be identified, described, and used in design processes.

This last section is the culmination of this work in that it provides a unified ontology of design representation and reasoning that affords the mixed use of affordance and function concepts in a structured design process. Using this ontology, designers can incorporate contextual knowledge, ‘soft’ requirements, relationships among user groups, technological interdependencies, and interconnections within and between these levels of description. This approach allows top-down and bottom-up design reasoning processes to be extended from their Function-Behavior-Structure roots to all aspects of the design problem including early stage and user-centric design processes.

The broader benefits of this affordance-based approach lie in their potential to foster Maier and Fadel's paradigm shift. A use-based approach focuses design effort on the material realities of goal achievement and situates the design and optimization of artifacts in a broader sociotechnical framework capable of directly capturing user needs in a systematic fashion. Building this framework with affordance theory allows designers to simultaneously adopt and integrate the languages and ontologies of ecological psychology, action theory, and function theory. Bringing these ontologies together links high level social and intentional information with low level technical knowledge in a way that makes explicit the links between design features and use processes throughout the product life-cycle. The representation and reasoning systems in this approach will help methodologists to structure their research and designers to broaden their search for design opportunities and solutions in the early stages of design.

We have sought to build on the successes of now well-established systematic design processes. Given the proliferation of lean and agile development processes and a renewed industry-wide focus on understanding users, we see the affordance-based approach as a natural addition to the design methodologist's and engineering designer's toolboxes. While the field of affordance-based design is still young, we hope our effort to clarify some of its foundational concepts helps researchers and practitioners benefit from the flexibility and power of the affordance approach.

5 INTEGRATING FUNCTION- AND AFFORDANCE-BASED DESIGN PROCESSES

In this chapter we explore the possibility of reconciling and integrating affordance- and function-based design methods. We present a classic function-based design method and discuss its strengths and weaknesses and argue for the benefits of augmenting it with the more recent affordance-based approaches. Building on existing function concept ontologies, we adopt a use-centric framework based on action theory and present an extensible, integrated approach to early-stage design processes. This approach combines the use of affordance and function to capture user needs across a device's life cycle. This provides designers with an array of descriptive tools tailored for different stages in the design process, thereby adding rigor to early-stage problem identification and requirements generation while maintaining the benefits of traditional function-based design processes. Application of the integrated approach is demonstrated with an example.

5.1 INTRODUCTION

Product design is an inherently multidisciplinary process. A product design effort might involve a diverse set of departments and individuals, including corporate strategists, marketers, industrial designers, design engineers, industrial engineers, manufacturing workers, interface designers, end-users, and others. Each of these participants in the design process brings a unique perspective to bear on the design problem at hand, drawing on knowledge gained from their own personal experience, education, and role in the organization. Engineering design is central to this effort, but traditional engineering design methods such as the German Systematic Engineering Design (Pahl and Beitz, 1996) are intended to solve the kind of well-defined technical problems that are often in short supply early in the design process.

Traditional engineering design methods are typically based on Simon's (1969) use of function, and so collectively suffer from a number of theoretical and practical issues. First, function-based methods are only applicable to certain types of problems and design tasks – namely, those that can be captured using input-output representations. Second, because of their reliance on input-output representations, function-based methods are difficult to use in early design processes when the design problem is not yet well defined. Third, it can be difficult to apply function-based methods consistently due to different understandings of the concept of function (van Eck, 2010).

Engineering design practitioners need tools that allow them to better interface with other design process participants during the up-front, ‘fuzzy’ stages, while retaining the benefits of these traditional tools. Maier and Fadel (2009a) present affordance-based design as an alternative design method. The benefits of affordances are in their ability to describe a broad range of requirements in a well-founded and intuitive fashion, particularly up-front in the design process.

Affordances have been used by researchers and designers in the fields of human computer interaction, architecture, and user-centered design, but despite increasing interest in the engineering design literature, affordances have seen little application in mainstream engineering design research or practice. Authors contend that affordance- and function-based design processes can coexist (Brown and Blessing, 2005; Maier and Fadel, 2009a), but little work has been done to reconcile these two processes such that the benefits of both might be maintained.

5.2 BACKGROUND

The goal of this chapter is to demonstrate one way in which function-based and affordance-based methods can be reconciled, integrated, and used across the design process in a mutually supporting fashion. Function is a foundational concept of engineering design, with almost all contemporary design processes considering the creation of artifacts possessing desired *functions* as the primary goal of the design process (Maier and Fadel, 2009a). In the following two sections, we provide an overview of function- and affordance-based design processes before suggesting a way in which they might be integrated to mutual benefit.

5.2.1 FUNCTION-BASED DESIGN

Pahl and Beitz’s *Engineering Design* (1996) is a canonical function-based engineering design process. In their work, functions are solution-independent specifications of the relationships between a system’s inputs and its outputs in terms of the flows of energy, materials, and information. Function definitions consist of verb-noun statements that describe what the system is supposed to do in terms of transformations of materials, energy, and information. For example, a vehicle’s drivetrain fulfills the function of *converting* a *flow of stored potential energy* into *translational effort* (Figure 9). Functions are decomposed into subfunctions until a sufficient degree of specificity is reached that known working principles or existing technologies can be directly identified, such as the conversion of *chemical energy* into *mechanical energy* by a gasoline internal combustion engine. This approach carries with it a number of limitations.

Certain problems are outside the scope of function-based methods, such as those involving aesthetics, passive solutions, or anything that does not require the transformation of matter, energy, or information. Maier (2011) provides examples of such problems, and demonstrates the difficulty of performing functional decomposition. Designers seem to encounter difficulty when trying to capture types of human-artifact and artifact-artifact interactions that are not well supported by functional representations. Requirements unrelated to transformations (especially transformations occurring during end-use) are captured by design requirement lists without a guiding foundational theory.

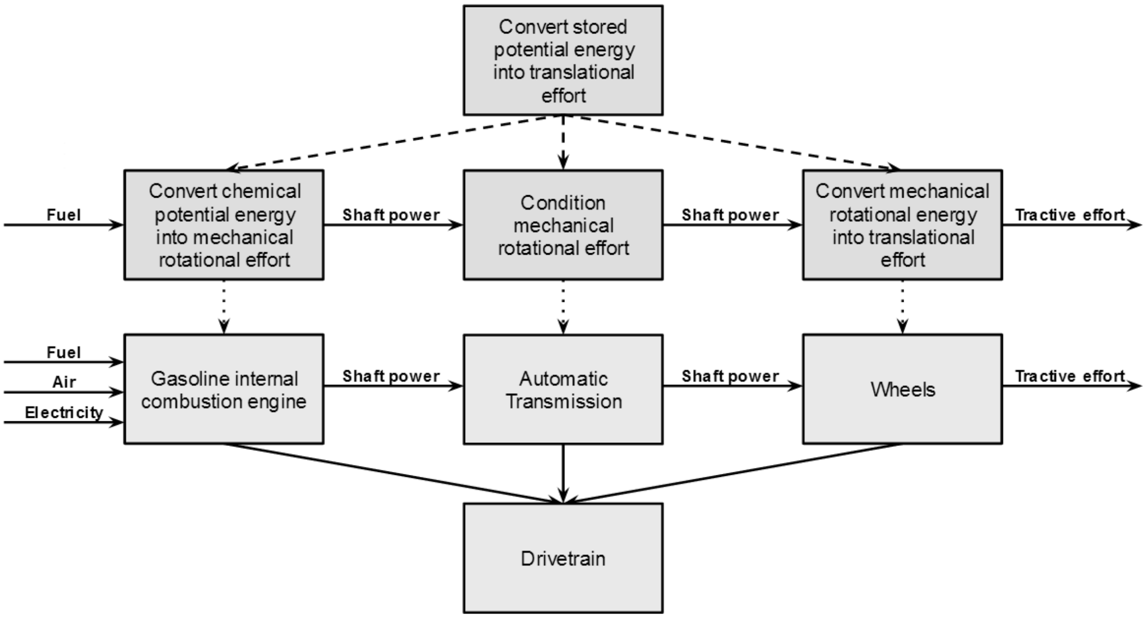

Figure 9: Structure of function representations

Using functions to represent device use has proven to be a non-trivial problem. Device-centric function modeling is only intended to capture device functions, but modelers and researchers apply function-based tools to user actions to more fully capture use cases (Burhan, 1998; van Eck, 2010).

Other researchers have encountered difficulty using function structures to represent nontraditional systems. Schultz *et al.* (2010) investigate the design of morphing airfoils, and identify ambiguities in function modeling approaches related to system boundaries and flow definitions, mutually transforming systems, simultaneous collocated functions, different operational states that cannot be represented in a single model, systems that defy black-box decomposition, and the translation of requirements into functions. Eckert *et al.* (2011) found that even experienced designers possess different, conflicting ideas of what function models are supposed to capture (semantic confusion), with some taking an internal, device-centric approach and others focusing on what goals the device can be used to achieve. Even when using well-developed device-centric methodologies (*e.g.,* Hirtz *et al.* (2002)), designers had difficulty identifying how device elements should be captured (syntactic confusion).

Despite these limitations, Pahl and Beitz's approach to function remains one of the key tools of contemporary engineering design. Transformation-based function definitions are an effective way to partition systems to reduce the complexity of the design task (Erden *et al.*, 2008). Function-structure diagrams promote systems thinking, providing an overview of how complicated devices and technologies work together to achieve goals, while abstracting away unnecessary low-level information. Functions form the basis of modular and product family design processes (Gershenson *et al.*, 2003). They allow designers to clearly identify key properties of system interfaces, allow subsystem-specific information to be segregated from overall system descriptions, and provide a way to represent and measure interdependency within and between systems (Khadke and Gershenson, 2008). Formal function representations have seen decades of refinement for design automation tasks (Gero, 1990; Siddique and Rosen, 1999; Kurtoglu and Campbell, 2006; Chakrabarti *et al.*, 2011). Functions can capture both spatial and temporal behavioral transformations of operands (Kitamura *et al.*, 2004). They are used as form-independent links between inputs and outputs, and can be used to identify mutually exclusive or competing solutions (Pahl and Beitz, 1996). Lastly, function-based techniques have seen widespread real-world use, meaning that there is a significant base of expertise, software support, and acceptance of function-based methods and theory throughout the design community.

Well established, useful tools are often difficult or impossible to replace – even if new technologies offer clear benefits. Maier and Fadel's (2009a) affordance theory seeks to address the major theoretical and practical gaps in function modeling, but does so in a way that offers no clear interface to traditional engineering design processes. Despite the methodological gap between the two strains of design theory, the two are not mutually incompatible. Even in their prominent critique of affordance-based design, Brown and Blessing (2005) argue that they "see a role for affordances in the design process in addition to functional reasoning." In the following section, we take a closer look at affordance-based design methods in an effort to connect them with function-based techniques.

5.2.2 AFFORDANCE-BASED DESIGN

Maier and Fadel's (2009a; 2009b; 2009c) affordance-based design is based primarily on the work of Gibson (1979) and Norman (2002). Drawing on the Gestalt psychology of Koffka (1935) and years studying the processes of human and animal perception, Gibson coined the term affordance to describe how organisms perceive and act in their environment: "the affordances of the environment are what if *offers* the animal, what it *provides* or *furnishes*, either for good or ill." Gibson himself was first to discuss the affordances of artifacts, tools, and useful things. Norman (2002) expanded this analysis in his landmark callout of bad design, identifying a number of design principles and rules of thumb to improve the usability of everyday items. Maier and Fadel further built on Norman's work, establishing a systematic engineering design approach intended as an alternative to function-based design.

Maier and Fadel's (2009b) process of Affordance-Based Design (ABD) bears many similarities to Pahl and Beitz's (1996) function-based Systematic Engineering Design. In particular, both systems establish a set of basic analytical principles that help designers navigate the process of identifying, defining, and solving a design problem based on insights from their respective fundamental concepts. Five affordance properties guide ABD's analyses – complementarity, polarity, multiplicity, quality, and form dependence – as well as two types of affordances – Artifact-User Affordances (AUAs) and Artifact-Artifact Affordances (AAAs). The five properties respectively mean that affordances are interactions between systems, that they can be beneficial or harmful, that any given system has multiple affordances, that some systems are better than others at affording certain behaviors, and that affordances depend on physical systems for their existence. AUAs describe the interaction opportunities an environment or artifact provides its users, while AAAs describe potential behavioral interactions between inanimate objects, such as subsystems of an artifact or between an artifact and the environment (Maier and Fadel, 2009b; Cormier *et al.*, 2013).

Performing the ABD process involves using these principles to construct a set of design requirements. Beginning with high level AUAs, the design problem is described in terms of what the user must be able or unable to do or what the artifact or device must provide the user. Complementarity implies that requirements should be described in terms of useful behaviors involving at least two systems, such as how a seat should *provide support* to a person or how a car's steering wheel must afford the driver the *ability to turn it*. Polarity allows designers to identify and describe both desirable behaviors (to be designed for, like *comfort*) and undesirable behaviors (to be designed against, like *wasting energy* or the *ability to hurt oneself*). Multiplicity highlights the fact that the artifact will have different affordances for different users with different goals and abilities (*e.g.*, those encountered during different life-cycle phases such as manufacturing, end-use, and retirement, or a car having both *passengers* and *drivers*), and the design must implicitly or explicitly account for all of them. Quality refers to the fact that systems can be evaluated based on how well they afford an action or behavior, and allows a design to be evaluated along as at least as many dimensions as it has affordances. Form-dependence means that affordance evaluation requires knowledge of the structure of the design[3].

Where AUAs provide a way to describe the external user interface, AAAs allow the designer to describe interactions between an artifact's *subsystems*, *components*, and its *use environment*, allowing ABD to be applied to mechanical design problems such as gear tooth profile optimization or vacuum cleaner design (Maier and Fadel, 2009b). After identifying affordances, ABD guides design optimization by highlighting how the quality of each affordance relationship depends on attributes of the involved systems. Users will possess certain resources and abilities, which can be augmented with tools or training, or artifact and component designs can be modified.

This approach complements and informs the one taken by Pahl and Beitz's Systematic Engineering Design by providing tools for early problem identification and requirements definition, a

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[3] Some authors such as Michaels (2003) take an even stronger approach, and argue in favor of a strict type of form dependence for sake of protecting the "true innovation of the affordance concept" which lies in "providing the origins of meaning and an experimental inroad for studying it." Hence, affordances should only be action opportunities directly perceived by the organism for whom the system afford action and "the perception of affordances for others … ought not qualify as the perception of affordances."

framework for describing and designing user and subsystem interactions, and a design validation framework that accounts for the entire product life-cycle. A broader look at the theory of design modeling shows that, despite their form-dependence, many important affordances (those involving intentional, goal-directed actions) capture information about user needs and device use at a higher level of abstraction than functions. Maier and Fadel's (2009b) affordance structures (Figure 10) and their matrix-based representations provide a tool that can capture interaction and interface information that is difficult to capture in function models, and thereby link function models, working principles, and embodiment designs to high-level requirements from across the product life-cycle.

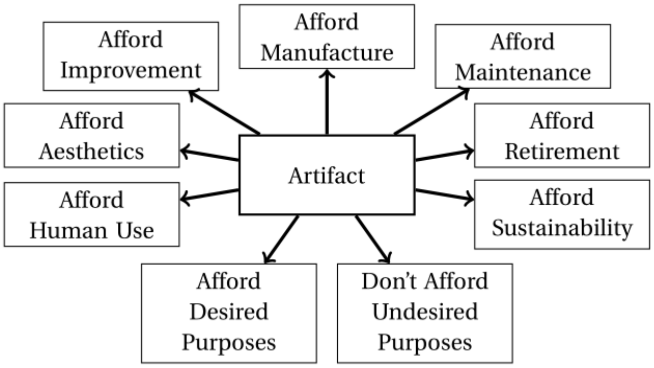

Figure 10: Generic affordance structure (Adapted from (Maier and Fadel, 2009b))

In the following section, we will briefly examine the theory of design modeling, seeking to situate affordances, functions, and their associated concepts within a common conceptual framework. In Section 5.4, we will examine the design process, and show how our integrated approach can be applied to the design process in a way that takes advantage of both systems. Finally, we will discuss the implications of this work and suggest avenues of future research.

5.3 DESIGN DESCRIPTIONS

Function models act as a bridge between descriptions of human intent (goals and purposes) and a device's physical behavior (Umeda and Tomiyama, 1995). Affordances are possible actions or behaviors, where actions are behaviors performed by an agent to achieve a goal. Though behavior links function and affordance, a more complete picture of design modeling concepts provides a more intuitive understanding of how to put their relationship to practical use. In this section, we demonstrate how a use-based design description framework can reconcile and integrate function and affordance-based design representations and processes.

Brown and Blessing (2005) use a detailed account of Chandrasekaran and Josephson's (2000) and Rosenman and Gero's (1998) function modeling frameworks to compare and contrast function- and affordance-based representations and reasoning processes in design activities. Brown and Blessing's framework highlights a number of often overlooked aspects of artifact use that allowed Vermaas (2009) to develop a more complete metamodel of these concepts. This metamodel integrates and evolves earlier approaches by using *goals* and *actions* to replace *purposes* (Gero, 1990; Gero and Kannengiesser, 2004) or *needs* (Erden *et al.*, 2008) in the set of intentional description types (Figure 11). Vermaas shows how descriptions of goals, actions, functions, behaviors, and artifact structures are linked by top-down, intentional design reasoning and bottom-up, structure-based behavioral validation. Together, goal, action, and function descriptions allow us to begin the reconciliation of function- and affordance-based design methods.

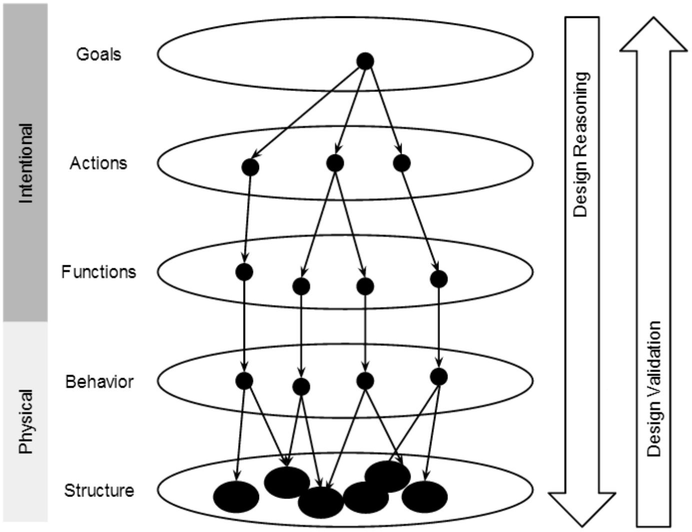

Figure 11: The five main design modeling concepts. (Adapted from Vermaas (2009))

Goal descriptions encode an individual's or an organization's reasons for acting in terms of the desired states they want to bring about, such as someone driving a car to work instead of bicycling to be on time for a meeting. Goals can be broken down into subgoals whose descriptions encode intermediate states necessary for the achievement of an overall goal. For example, in order achieve the driver's overall goal of *being at work*, one first has to achieve the goal of *being in the car*, then the car must *be running,* and the driver-car system needs to *be in motion on the freeway*. As shown in Figure 11, these goals are linked to the actions by which they are achieved – *being at work* is achieved by the action *going to work,* which may be done by using a car and executing a plan that includes including *getting into the car*, *turning the car on*, and *driving on the freeway*. The purpose of representing user goals in the design process is to capture the reasons why users are executing a plan or performing certain actions, providing a purposive context to inform decisions regarding device functions, behaviors, and structures.

Action descriptions encode opportunities for actors to transform one situation into another. In any given situation there are a number of afforded actions that a user can perform – a driver that has entered the car can *turn the car on*, or they can *get out of the car*, or they can *shift into neutral*. Describing a design in terms of actions can involve enumerating a use plan (*e.g.*, according to (Houkes and Vermaas, 2010)) – that consists of a list of possible actions including device manipulations and effects that will allow a user to achieve a goal state from some initial state. Pols (2012) shows how a particular afforded action can be described in terms of an opportunity for activity (abstract social action, *e.g., going to work*), a use (*driving the car* from *point A* to *point B),* or one or more physical manipulations (*actuating* the *gas pedal, brake pedal,* and *steering wheel*) or effects (*accelerating, decelerating, turning*). Pols writes that to realize a system function the designer should describe the function in high-level affordance terms as an activity or use opportunity, and see to it that the system possesses the necessary manipulation and effect opportunities to perform the activity or use process. Descriptions of manipulation and effect opportunities allow designers to link actions with functions (Figure 11), by using device-centric function descriptions to capture reliable connections between manipulations and effects. Design validation at the action level involves ensuring the available action opportunities allow the user to realize their goals.

Function descriptions encode useful device behaviors. Pahl and Beitz's approach captures functions in terms of labeled input-output relationships, and is intended for describing internal, device-centric functions as opposed to external, environment-centric effects (Erden *et al.*, 2008). A device-centric description of an engine might be *convert flow of fuel into shaft power* while an environment-centric description might be *apply torque to the transmission,* or *linearly accelerate the driver*. In the environment-centric description, the behavior occurs somewhere outside of the engine, involves the engine's connections and interactions with the rest of the system (Chandrasekaran and Josephson, 2000), and must be described relative to that system at the appropriate level of abstraction (Crilly, 2012). Engineers find both device- and environment-centric descriptions to be useful (Vermaas, 2009; Eckert *et al.*, 2011).

Affordance language supports the design of device-centric functions when used to capture manipulation and effect opportunities local to the device, such as manipulation of the gas pedal and the effect of increasing engine torque. Affordance language supports the design of environment-centric functions in two ways. First, it can describe what behavioral relationships should be possible between adjacent systems, *e.g.*, the engine should afford *provision of shaft power* to the transmission and the vehicle as a whole should afford *provision of motive force* to the driver. Second, it can describe what effect opportunities should be available without reference to a particular device – such as the opportunity to *indicate one's intention to turn* to other drivers. (Galvao and Sato, 2005) present a matrix-based technique based on affordances to model the involvement of device functions in goal achievement.

Design validation at the function level involves making sure that users are presented with the appropriate manipulation opportunities, that the device converts the appropriate device manipulations into the desired device effects, that the device effects can cause the desired environmental effects, and that these functions allow the user to perform their desired actions. Reasoning from function to behavior can involve flow descriptions, in which matter, energy, and information describe interactions between different systems – the means by which manipulations and effects are performed.

Function flows describe boundary conditions between functions in a function structure and between components in a component structure, and are a high-level tool for representing interfaces and interactions (Pahl and Beitz, 1996). Flows can be used represent both manipulation and effect opportunities, and describing them as such allows designers to map actions to traditional function structures such that functions describe "reliable connections" (Pols, 2012) between device manipulations and effects. For example, while driving, manipulating the gas pedal with a flow of *human force* should reliably result in the effect of *acceleration*.

Goal, action, and function-flow descriptions encode a limited amount of behavioral information that serves as validation criteria for more detailed representations. In Pahl and Beitz's method, working principle, embodiment, and detail designs encode progressively more information about the design's behaviors and structure, and in Maier and Fadel's method artifact-artifact affordances can encode information about flows, behavioral interactions, and physical interfaces. Evaluating the behavior of these structures allows designers to ensure that subsystem functions can be performed, that those functions allow execution of a use plan, and that execution of the use plan will achieve the desired goals. For example, an automotive engineer might develop a systems dynamics model based on an embodiment design to simulate a vehicle's expected behavior and ensure that an idealized driver could use the vehicle to execute a particular use plan.

Bringing function and affordance descriptions together in the context of their respective design processes results in a descriptive and representational hierarchy that embeds traditional, device-centric design tools in a use-centric framework (Figure 12). Each level of description (goal, plan, action, function, working principle, and embodiment) describes in increasingly greater detail the behaviors the system should afford the user or other artifacts and the requirements that must be met for it to do so.

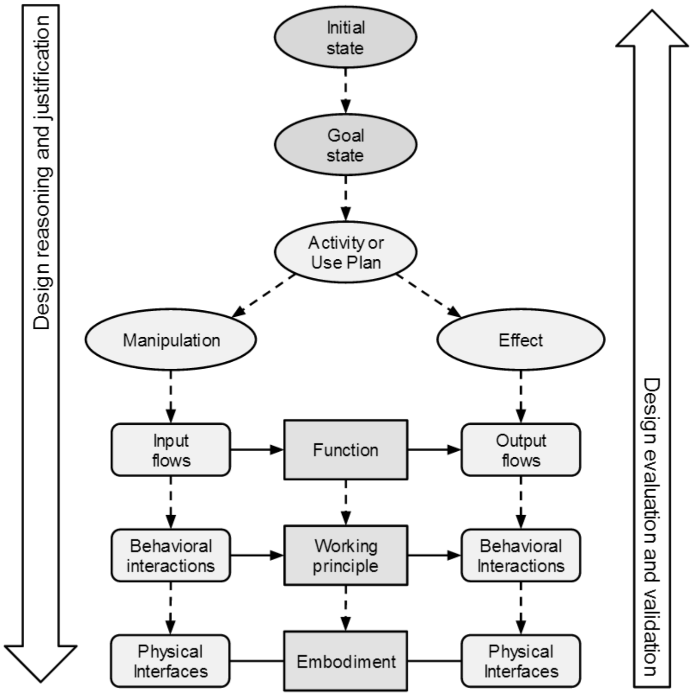

Figure 12: Overview of the combined model. Initial and goal state descriptions feed into the affordance descriptions. The outer affordance descriptions (rounded rectangles) are connected by device descriptions (regular rectangles). Function-based device models thereby capture the "reliable connections" (Pols, 2012) between manipulations and effects.

In the diagram, the initial and goal nodes are situations or states captured with descriptions of users, resources, devices, objects, environmental features, social information, and intentional facts such as user goals. The activity, manipulation, and effect nodes (and those immediately below them) are afforded actions, behaviors, abilities, and relationships encoded in the system's affordance structure. Based on particular initial- and goal-state pairings, plans for goal achievement are developed as ordered or partially ordered lists of actions, including some that are described in terms of manipulations and effects. When device functions are required to realize an effect or behavior, Pahl and Beitz's systematic tools can be put to use. Green nodes are device descriptions, and can be encoded using traditional function-based tools such as function structures and design structure matrices at a high level, followed later in more detail by sketches, prototypes, mathematical models, computer simulations, solid models, and physical prototypes. The specification of behavioral and structural interface requirements among functions, subsystems, and components may exist in both the device descriptions and the previously discussed affordance structure, linking function- and affordance-based representations. Use in the early design process

Pahl and Beitz (1996) roughly decompose design processes into four steps: problem definition, concept design, embodiment design, and detail design. Each step generates information used to perform the next portion of the design process. Problem definition includes the 'fuzzy front-end,' in which design opportunities are identified, high-level product concepts selected, and lists of requirements generated as the design task is clarified. Concept design involves the ideation and selection of working principles, while embodiment design involves integrating the selected working principles into a coherent design by "determining the general arrangement and preliminary shapes and materials of all components" (Pahl and Beitz, 1996). Detail design turns the embodiment-level description into a manufacturing-ready design specification.

In the following sections, we demonstrate how a combined affordance- and function-based processes address the 'fuzzy' problem definition and concept design phases. In problem definition, affordances are used as a high-level, foundational concept to support problem definition and task clarification by capturing goals, requirements, and existing resources and abilities across the product life-cycle. Function-based design provides concept design tools that aid the decomposition and development of complicated system architectures while still mapping neatly to affordance-based representations.

5.3.1 PROBLEM DEFINITION

Pahl and Beitz describe a product planning process performed to identify design opportunities relevant to a company's goals based on high-level, strategic considerations. Design opportunities are sought based on corporate needs, current capabilities, user needs, market position, technological trends, and expected future developments, such as the absence of an affordable all-electric vehicle on the market coupled with technological and market readiness for one. Designers traditionally identify product ideas by evaluating existing function structures, working principles, embodiment designs, and system structures before selecting and elaborating upon one or more concepts to develop a solution-independent requirements list.

The affordance-based problem definition process supports high-level planning and problem-definition processes by providing a link from high-level strategic goals to lower-level tactical concerns. Treating each phase of the product life-cycle as a type of use process allows the analysis of the design problem in terms of how different types of users interact with the product in pursuit of individual and collective goals (Figure 13). Designers document the problem in terms of what goals each type of user needs to be able to achieve, and affordances are documented in terms of the actions the users must be able or unable to perform (Maier and Fadel, 2009a). For example, if planners have identified the opportunity to design, manufacture, and market the affordable electric vehicle then strategic marketing and business concerns motivate the project, while the logistics of design, manufacturing, and end-use determine project feasibility and constrain the specification of the design problem.

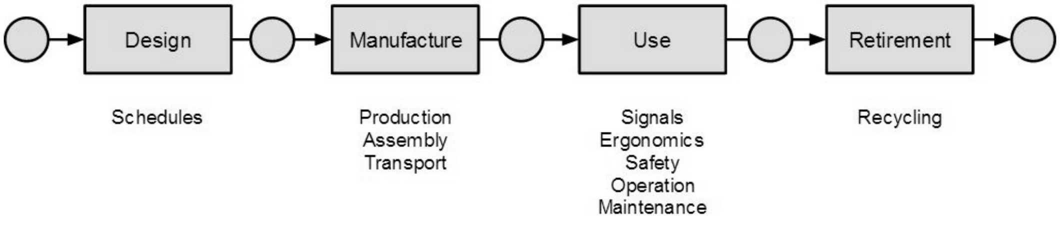

Figure 13: Pahl and Beitz's top-level requirements mapped to a simplified set of product life-cycle processes

The goals of the design process are determined by the high-level strategic concerns. Designers map strategic goals to the various life-cycle processes in which the goals must be achieved and plans for their achievement are developed. At the intentional level (Figure 11), the design process can be understood as planning the actions that will bring about goal achievement. Participants in the design process make use of the affordances of their environment to perform this process, including those provided by design representations (Gero and Kannengiesser, 2012), prototypes, and other designers. The resources required to develop the design of an electric vehicle are different from a conventional petroleum-fueled design, requiring knowledge of batteries, motors, high-voltage electrical systems, and the challenges involved in their integration. Planning the design process requires understanding the interrelationships between the design sub-processes associated with each sub-system and how these systems will come together to provide use opportunities.

Describing the participants in the manufacturing process, their goals, plans, and the low-level affordances they require guides designers to address design-for-manufacture concerns throughout the design process. The overall goal of the manufacturing process is artifact production, achieved by workers and managers using the affordances of the manufacturing environment. Logistically, the manufacturing process relies on environment-afforded inputs of materials, energy, and information, and their specification is part of the problem definition processes. Material inputs include raw materials, pre-manufactured components, subassemblies, facilities, machines, and tools. Energy is provided in the form of flows of electricity, fuel, and labor. Information includes the specifications developed during the design phase, along with skills, regulations, and procedural information. For an electric vehicle design to afford manufacture there must be a sufficient supply of materials like lithium for high-voltage battery packs, energy to operate equipment and facilities, and design specifications must have accounted for each manufacturing process such that workers are able to manufacture and install the batteries in the vehicle.

Developing high-level affordance structures based on the stages of a product's life-cycle highlights dependencies between goals, action opportunities, behaviors, and material structures. Problem definitions and design decisions must take these dependencies into account, and the process of their analysis can be mapped according to Gaver's (1991) sequential and nested affordances. Sequential affordances are actions, behaviors, and states that must be realized serially to achieve a goal (such as when one action must be performed before the next action becomes possible) while nested affordances are those that afford a particular action only in combination. For example, the company's supply chain must afford workers the components and materials that give them ability to manufacture the vehicle before it can afford use to end-users. Realizing the former affordance (ability to manufacture the car) creates possibility of the latter (the opportunity to drive the car), and the sum of the affordances of the manufacturing facility are required to perform the manufacturing process. Sequential affordances can be used to understand and describe linear dependencies between actions and behaviors, while nested affordances can be used to understand and describe nonlinear dependencies.

In this fashion, affordances and life-cycle processes organize the early documentation of design requirements. Pahl and Beitz provide a design requirements checklist with seventeen main headings, three of which (energy, material, and signals) apply to input and output flows of functions or functional systems, four (forces, kinematics, geometry, and material) apply to device behavior and structure, and the rest map to phases of a product's life-cycle (Figure 14). Over the course of a design project, each of these requirement categories is further decomposed until it becomes possible to directly identify the conditions that must hold for a particular process, action, or behavior to be afforded.

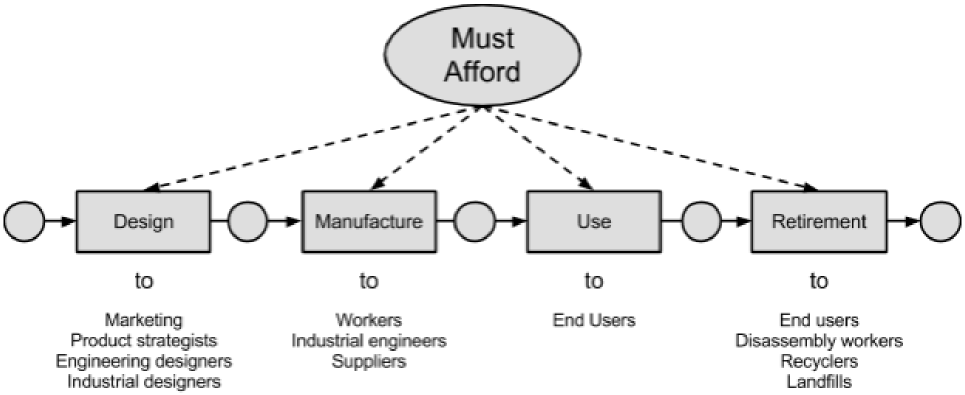

Figure 14: Affordances exist across a product's life-cycle

The addition of the life-cycle perspective of affordance-based design supports Pahl and Beitz's task clarification and requirements generation processes by providing additional guiding structure to designers. Pahl and Beitz write that practical difficulties often arise while generating requirements, including ignoring "obvious requirements" (*e.g.*, ease of assembly), not updating requirements lists throughout the project, not having a plan for refining imprecise requirements, and incorporation of function- or solution-specific requirements too early in the project. An affordance-based approach to requirements identification guides designers to incorporate requirements from all phases of a device's life-cycle and address all users, reducing the likelihood that important requirements will be missed. A hierarchical affordance representation cast in terms of what users *need to be able to do* from goal achievement down to specific physical interactions allows high-level requirements to be refined and linked to low-level requirements throughout the design process, promoting requirement list updates and stepwise refinement. High-level requirements described in terms of goals, states, and action opportunities allow (require) designers to describe what is necessary in a solution-independent fashion, while providing clear links to function-, behavior-, and structure-based requirements.

5.3.2 CONCEPT DESIGN

Once the design problem has been clarified, concept-level design involves "the establishment of function structures, the search for appropriate working principles, and their combination" (Pahl and Beitz, 1996). Function structures in SED are created from the top down (through decomposition of an overall function) or from the bottom up (by ascribing functions to an existing system) based on input-output relationships and verb-noun function descriptions. Once sufficiently detailed function structures have been constructed, solution concepts are generated by identifying a number of working principles for each function and combining principles to create complete concepts. These concepts are refined until they can be compared for technical and economic suitability.

While affordance-based design does not explicitly provide tools for concept generation, affordances can guide concept design processes by providing a higher-level design perspective. Once a goal-level affordance has been identified, its means of realization can be identified through action and function decomposition. High-level affordance descriptions, *e.g.,* opportunities for activity or use, are broken down into progressively lower-level descriptions until they can be expressed as a set of manipulation and effect opportunities sufficient for goal achievement (Pols, 2012). When device functions are necessary to connect these manipulations and effects, different candidate function structures can be generated.

Much like how function models allow systematic identification of multiple working principles to instantiate each function (Pahl and Beitz, 1996), action-level affordance descriptions allow the identification of multiple function level solutions by describing afforded behaviors in terms of flows. An existing function-level description of a powertrain might involve converting a flow of *chemical energy* directly into *mechanical energy* based on a controlling flow of *human force*, while another might involve converting *chemical energy* into *electrical energy* – controlled by the same *human force* manipulation – before converting the *electrical energy* into *mechanical energy*.

Once an appropriate function structure has been identified, traditional tools can be used to refine the design concept. As this process progresses, the behavioral and structural interfaces between functional subsystems can be described in terms of increasingly lower-level affordances. Since functions and subfunctions are defined in terms of their inputs and outputs, we note that the artifact-artifact affordances (AAAs) of Maier and Fadel (2009b) neatly describe the nature of the flows that connect subfunctions (Figure 15). For example, say device function F1 connects a manipulation to an effect but requires further decomposition before working principles can be easily identified. Decomposing F1 into two subfunctions F1.1 and F1.2 connected by an intermediate set of flows results in an AAA that represents the behavioral requirements that F1.1 and F1.2 must maintain for compatibility. If the AAA is a flow of *electrical energy* generated by F1.1, F1.2 can only be realized by working principles that when driven by flows of electricity provide the desired output AUA. Flow definitions serve to constrain the selection of functions and working principles.

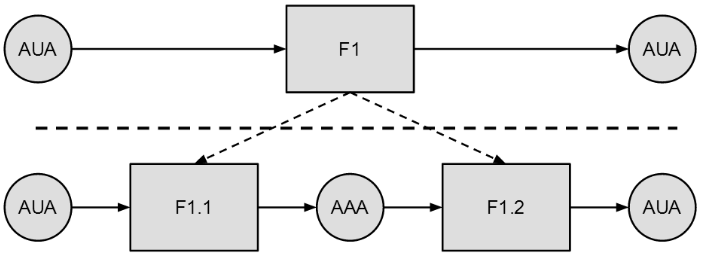

Figure 15: Subfunctions are connected by artifact-artifact affordances

At the end of the concept design phase, the fitness of each conceptual variant is evaluated and the strongest design is chosen. The affordance principle of quality implies that quality metrics apply at each level of description, from goals through to physical interfaces. Plans that involve less actions or lower-cost actions may be higher quality options than more complicated versions. In some circumstances users may prefer – or it may be more feasible or economical for them – to manually achieve goals instead of designing more complicated functional solutions, such as with manual versus automatic transmissions. Affordance-based quality analysis implies that designs should be evaluated based on how well they contribute to each process of goal achievement during each phase of the life-cycle. (Maier and Fadel, 2009b) suggest limiting the number of comparison criteria to between eight and fifteen in number. Given the potentially large number of affordance relationships, only the most important are likely to be selected for evaluation, and at this point there should be a clear link between the chosen factors and the initial high-level requirements.

When taken together, the affordance- and function-based design approaches describe a design process that addresses the achievement of goals across the product life-cycle by analyzing both user actions and device functions. While a design specification in the form of engineering drawings may still be the primary output of the design process, the combined approach ensures that it was developed in concordance with a variety of goals and use contexts. In the following section, we will reiterate the automotive example referenced above, and demonstrate explicitly how affordance- and function-based processes flow into and support one another, followed by a discussion of how this combined approach can provide designers with abilities that are beyond either when taken alone.

5.4 EXAMPLE USE

In this section we demonstrate how this system might be used to structure representations in a use-based design process, starting from a high-level problem description and progressing to the low-level identification of relevant design concepts and design variables. We reiterate our going-to-work and electric vehicle examples, adopting a high-level, early-stage design perspective to demonstrate the reasoning processes an affordance-based approach provides to use-centric design.

We start our design process by identifying a user type and establishing a prototypical use case that allows us to catalog design-relevant information as it is generated. In this case, our target user is a *worker* who wishes to *get to work (*Figure 16). Since *going to work* is something that happens often, we assume that the worker wishes to minimize the cost of going from home to work, and define the boundary conditions of this early analysis to include only this case (*e.g.*, for cost/benefit accounting purposes). Identifying the user, their initial situation, and their goal situation provide us a set of basic elements that provide the foundation of the affordance structure. Each of these elements can be elaborated upon with specific information such as user abilities, resources, locations, times, and environmental conditions.

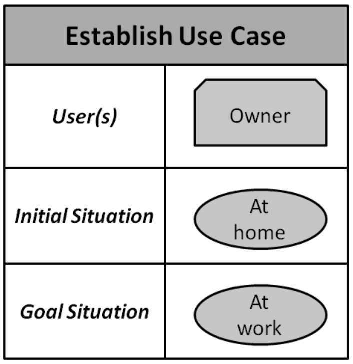

Figure 16: A situation in which a user wishes to achieve a goal defines a use-case.

Once a use case is defined at the user and goal levels, an initial situation and goal situation are paired to allow the development of a use plan. A particular use plan describes how to get from a specific initial condition to a specific goal condition, and its elaboration involves description of the objects, environmental features, and needed or desired afforded actions. As with the elements of the use-case description, the object, feature, and action elements of a use plan can be elaborated upon, and in early stages or at a high level represent placeholders or templates for generating more complete representations. In this going-to-work situation, the user can conceivably take advantage of any resources at their disposal. If the goal of the team is merely to identify the 'best' way for the worker to get from home to work, then they may analyze a variety of object and plan types to arrive at the optimal solution. For example, a plan for going to work may involve walking, riding a bicycle, driving a car, taking the train, or a combination of these. If the strategic goals of the design team involve a particular type of artifact (such as a car) then the design space is narrowed – otherwise, designers can explore a variety of solutions at the object level.

If we are designers who are part of an automotive company, we are interested in workers who get to work using cars and can narrow the design space and develop a basic *driving-to-work* use plan. At the object level, we note that the worker will use their car, their key, and the roads that connect their home and workplace. In Figure 17 we describe a rough set of basic actions that will allow them to get from one place to another while negotiating traffic and the road network.

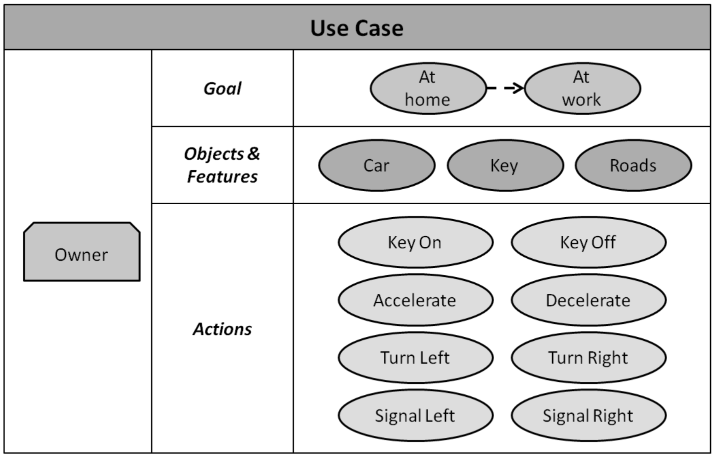

Figure 17: Use plans are described in terms of goals, objects, and actions

In this case, we choose to analyze the *accelerate* action (Figure 18). In affordance terms, we might say that the vehicle must *afford* or *provide* the driver with the *opportunity to accelerate*. The act of accelerating, like each of the other actions, can be described in terms of its social nature, use, manipulations, and effects (Pols, 2012). If we analyzed it in the context of a plan for highway driving *acceleration* might count as *passing*, but for the moment we ignore the social dimension and simply focus on its physical aspects. An *acceleration* action is physically initiated when the driver *manipulates the position of the accelerator pedal* of the vehicle, which reliably causes the effects of *tractive effort between the wheels of the car and the surface of the road* and *acceleration of the driver* herself.

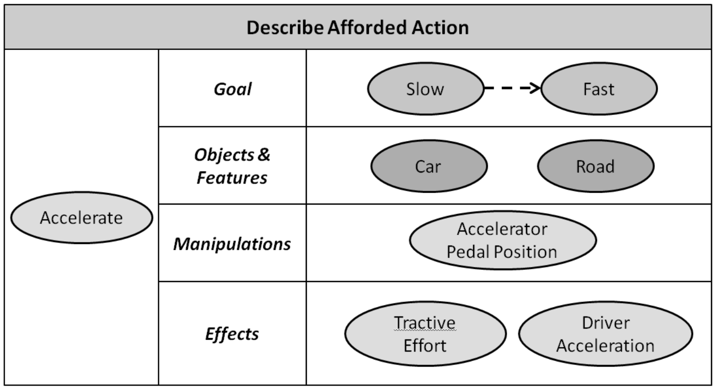

Figure 18: A particular action is performed to achieve a goal, and is decomposed based on the interacting systems, manipulation opportunities, and effect opportunities

At this point, we move from the action level to the function level of description to take advantage of function-based design tools. The first step in this process is to map the manipulation opportunity to the desired effect, which in our case is a desire for the opportunity to manipulate the *pedal position* to count as an opportunity for the driver to accelerate. We define this effect in terms of *driver acceleration* as opposed to *vehicle acceleration* first because the goal is to get the driver from home to work (not the car), and second because this approach allows both manipulation and effect to be described in terms of AUAs. Describing the action in terms of AUAs means that both manipulation and effect opportunities are directly experienced and perceived by the user and can be analyzed in terms of user attributes.

To perform this mapping from manipulation and effect opportunities to a function model, we identify a representative variable that captures the interactions between the user and vehicle. Here, we model accelerator pedal position as a *linear distance*, *X* and model driver acceleration with *motive force, F.* The variable *X* represents a flow of information from the user to the artifact, and the function of the artifact can be captured as *conversion of pedal position X into motive force F* (Figure 19). Since this function is rather high-level and abstract, it makes sense to decompose it into two subfunctions that describe how it is to be achieved. Here we split the overall function into a *position to torque* conversion and a *torque to force* conversion, which allows us to begin exploring further functional decompositions and identification of design concepts for each function. By including *torque* as the mediating flow between the two subfunctions, we have specified an Artifact-Artifact Affordance that can be analyzed in terms of parameters of the functional systems on either side of it.

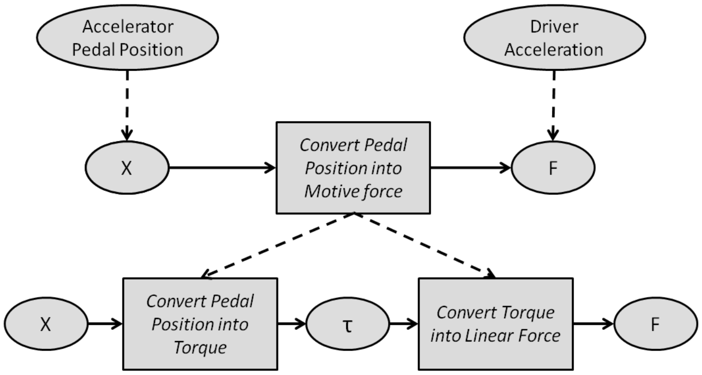

Figure 19: Manipulation and effect opportunities are mapped to function inputs and outputs

At this point, the affordance-based approach guides designers in modeling the implications of their function-based design decisions first by providing a comparison and validation framework and second by guiding comparative life-cycle analysis. By pursuing the design of the first subfunction in Figure 19 (*convert position to torque*), we can begin a search for working principles according to the systematic approach of (Pahl and Beitz, 1996). In this case, we can identify various powertrain types (*e.g.,* gasoline, hybrid-electric, all-electric) and can begin the combinatorial exploration and analysis of their subtypes and configurations.

We find that each of these candidates is already embedded in a validation framework since their provision of the ability to *convert position into torque* allows downstream systems to *convert torque into force*, and that force represents an artifact-user affordance. This allows us to evaluate the quality of each variant based on whether it is capable of *actually accelerating the driver when the pedal is pressed* and how well the driver perceives it to do so. We can then work our way back up to the use plan level and begin to discriminate between different situations in which acceleration is desired within a single plan or between different plans (Figure 20).

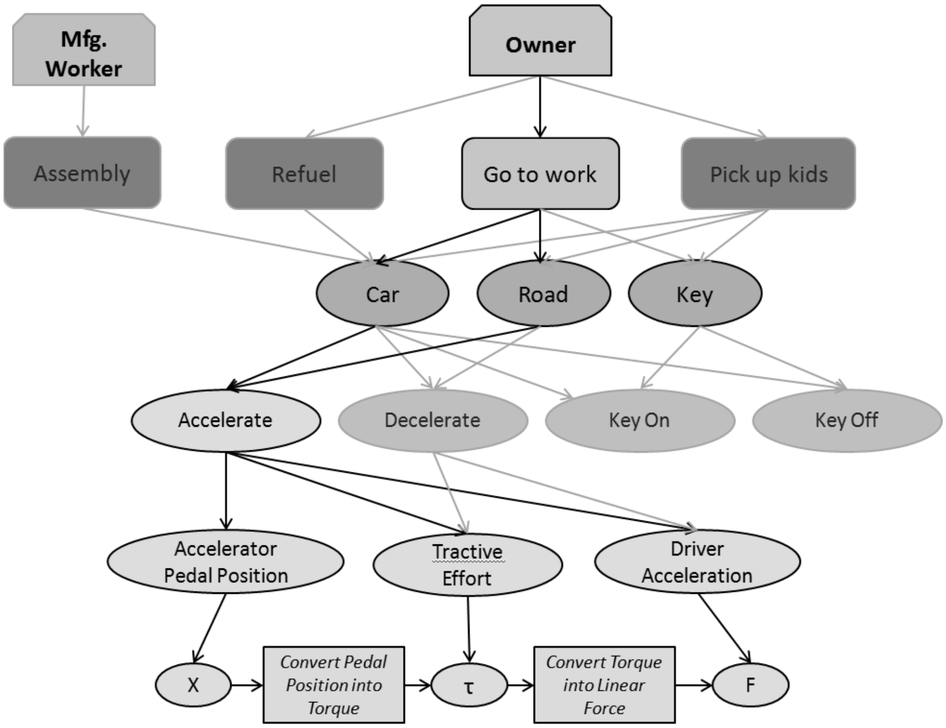

Figure 20: Low-level design decisions can be evaluated relative to any actions, objects, goals, or users with which they are involved

Likewise, we can broaden the scope of our analysis beyond the initial use case to assess other life-cycle phases in terms of users, actions, objects, and goals. For example, plans for the manufacturing phase of a gasoline design and an all-electric design will be significantly different. By describing each life-cycle phase in terms of use plans we can identify instances of affordance commonality (*e.g.*, actions performed by multiple user types) and differences between designs and embed their analysis in a similar structure. In Figure 20 we show how multiple use analyses can be overlaid on each other to understand interrelationships between functions, affordances, objects, goals, and users. For example, the *accelerate* action has the *tractive effort* and *driver acceleration* effects in common with the *decelerate* action. This approach allows one to track when low-level design decisions (at the function, working principle, or embodiment level) are likely to impact certain actions, affordances, and plans by following the connections between levels of description and identifying object and action involvement in multiple plans.

5.5 CONCLUSIONS

In this chapter we have sought to reconcile and integrate use of the function and affordance concepts across the design process by adopting a use-centric approach to design. By embedding function-based design processes within an affordance-based approach to artifact use designers can more fully capture the ‘fuzzy’ contextual information that is critical in the early stages of design while still using the powerful design tools with which they are accustomed.

The goal of reconciling the two methods is to address outstanding confusion as to the proper role of functions and affordances in the design process. While previous work has treated the two terms as representing competing approaches, in this chapter we showed that the concepts of function and affordance can play very different roles in the design process. We demonstrate that functions are best used to describe the intended behaviors of possibly large or complex subsystems, and that function-based design methods can be used to decompose these systems until direct solution identification is feasible. We likewise demonstrate that affordances are best used to describe what users must be able to do with the functional systems, and show how these descriptions can be organized using action-theoretic models of goal achievement.

Integrating function-based and affordance-based methods required identifying situations in which information used to specify artifact functions overlaps with information used to specify affordances. We identified that this occurs at the input/output boundaries of the black-box subsystems found in function-based design methods, and showed how affordances described in terms of manipulation and effect opportunities can be mapped to these interfaces. Once this mapping is performed, the lower-level function-based descriptions are embedded within use plans that can explicitly capture situation and goal information that contextualize the artifact's performance of the function.

In addition, we discussed how this approach can be applied throughout the design process and to the entire product life-cycle. Due to its focus on the end-user, affordance-based design provides powerful tools for the early stages of the design process, including concepts and language for requirement generation in terms of goal achievement and user interaction with the objects and features of their environment. Since affordance-based design lacks dedicated tools for concept generation or the design of product architectures, we identified a way to transition to a function-based approach after this initial stage. This process of applying affordances to high-level, intentional concerns before using functions to address the design of lower-level device behaviors can be applied to any stage of the product's life-cycle by treating other environmental objects and features such as artifact components, tooling, and machinery in the same manner as the artifact itself.

This work represents a first step towards a more robust, integrated design method. While (Pahl and Beitz, 1996) represent a canonical function-based design approach, there exist many other methods and theories that may yet benefit through integration with the various affordance-based design theories. We hope that this work will spur other researchers to look more closely at ways in which theoretical and methodological cross-pollination can occur.

6 TOWARDS AN ECOLOGICAL APPROACH TO ENGINEERING DESIGN

The field of ecological psychology is a branch of ecology that deals with how organisms are able to perceive, act, and achieve goals in a complex environment, and its chief theoretical contribution has been the concept of affordances. Affordances are not new to the world of design theory and methodology. While affordances have been used to analyze portions of the design process and develop practical design methods, this chapter posits that an explicitly ecological approach to engineering design allows for the realization of the full potential of affordance theory in this new domain. Affordances are relational properties of the objects, artifacts, and other features of the built and natural environment. In this chapter we use affordance theory to describe the process of design and manufacturing in terms of the creation, destruction, and modification of affordances. We suggest how our technique might be used to integrate existing design methods and methodologies as well as guide the development of future tools and research paths. Using such techniques will enable design researchers to systematically describe, evaluate, and improve processes throughout the artifact life cycle.

6.1 INTRODUCTION

The field of ecological psychology is a branch of ecology that deals with how organisms are able to perceive, act, and achieve goals in a complex environment, and its chief theoretical contribution has been the concept of affordances. Because affordances have only recently been imported to the field of design theory and applied the development of design methodologies, the vast majority of design-theoretic systems lack an ecological or affordance-based analysis. Our goal in this chapter is to demonstrate how affordance theory and the ecological perspective have the potential to guide and inform design research across the design and product life cycle.

The ecological approach is, above all, a framework for identifying, analyzing, and describing the goal-seeking behavior of organisms (Michaels, 2003). Originally developed by Gibson to understand better the role of visual perception in the performance of tasks by humans and animals, the ecological approach and its theory of affordances have proven applicable across a broad set of fields at varying levels of abstraction. These approaches have been successfully applied in empirical studies by behavioral psychologists and successfully put into practice by design theorists, architects, roboticists, and interaction designers.

In section 6.2 we discuss the history and current state of affordance-based design, and present the reasoning behind adopting a broader ecological framework. In section 6.3 we discuss the foundational principles of our ecological approach to design. We identify four as critical, including broader system boundaries, perceptual realism, recognition of technological ecosystems, and use of affordance-based reasoning. In section 6.4 we use these principles to develop an ecological approach to design based on the concept of ecological niches. We present the ecological definition of niches as collections of affordances and affordance carriers that allow the achievement of goals, and discuss the creation of artifacts in terms of niche alteration. In section 6.5 we use action theory to develop a goal-based approach to comparing niches and defining niche boundaries. Finally, in section 6.6 we apply this model to a generic design ecosystem, demonstrating how the ecological approach and niche analysis can be used to identify, evaluate, and improve the affordance-based relationships between methodologists, designers, users, and artifacts.

6.2 AFFORDANCE-BASED DESIGN

Researchers have applied affordance theory to individual problems within the design process to good effect. Authors such as Norman (2002), Maier and Fadel (2009a; 2009b), and Galvao and Sato (2005) have developed tools and techniques to help designers ensure that their designs possess affordances that end-users need or desire, do not possess affordances that are harmful or unwanted, and communicate the existence of those affordances to the user.

Even though this research program has provided theories (Maier and Fadel, 2009a; Pols, 2012), procedures (Galvao and Sato, 2005; Maier and Fadel, 2009b), and representations (Cormier *et al.*, 2013) to address the design of artifacts and systems, only preliminary work has extended the ecological perspective to include the niches of the designer or design methodologist. The best example of this work has been that of Gero and Kannengiesser (2012), who analyze the affordances of design representations – information-generating actions that different representational systems allow designers to perform given the "experience, interpretations, and goals of the designer." Gero and Kannengiesser demonstrate that the iterative selection, use, and refinement of design tools by designers during the design process has a clear effect on the evolution of the design, the design task, and the knowledge and expectations of the designer.

An ecological approach to engineering design does not imply a rejection or criticism of the tools, techniques, and methods that design theorists and practitioners have developed and used in the forty-plus years since the publication of *Sciences of the Artificial* (Simon, 1969). The key to the ecological approach is “the belief that success on practical problems involving the perceptual control of action is an important, perhaps the most important, way to validate the consistency and the significance of one's theory and research,” to the degree that “this commitment qualifies many to contribute as ecological psychologists, even though they call themselves by other names” (Shaw *et al.*, 1995). To this extent, any design methodology, method, or tool that yields practical results based on an understanding of the “perceptual control of action” suggests an opportunity for an ecological analysis.

For us in the field of engineering design theory, a theory of design or design method can be called ecologically valid if it accurately models or supports the manner in which its subjects or users go about their business of achieving design-related goals. Striving for ecological validity in engineering design means considering the tools and methods of the field from an embodied, user-centric perspective, with design methodologists and designers considered from the same perspective as traditional end-users. It means embracing the phenomenology of ecological psychology and applying it to the design, manufacture, and use of artifacts.

6.3 THE ECOLOGICAL APPROACH

As a branch of design methodology, the ultimate goal of the affordance-based design research has been to give designers improved design tools and processes. Towards this goal, researchers have appropriated the affordance concept from the field of ecological psychology as an alternative or complementary concept to function so as to take advantage of its unique meaning and roles in design reasoning.

Understanding the design process and product life cycle from the ecological perspective has received relatively little attention, though it has a number of implications for studying the design process.

First, the ecological perspective implies the analysis of an ecosystem as a whole, which requires a different approach to setting the boundaries of the design system to be analyzed. An ecological approach is holistic or even anti-reductionist, and instead of seeking to identify the most central tasks, processes, or individuals in the design process, an ecologically-minded design theory focuses more on how the various parts of the system interface and work together to achieve overall goals.

Second, the ecological perspective implies a commitment to realism and the analysis of real-world actions, behaviors, and interactions. The goal of an ecological analysis of design or industrial activity in general is an understanding of the real-world conditions that make it possible for people to frame problems, design solutions, and manufacture artifacts. In other words, it is clear that the world affords the creation of artifacts in a commercial setting and we want to understand the structure of this affordance relationship.

Third, the interdependency and coevolution of artifacts, technologies, and the built environment demonstrates that the social network of individuals and organizations that exists in the industrial environment is paralleled by and intertwined with an equally complex technological ecosystem.

Fourth, the analytical foundation of the ecological perspective is the concept of affordances. While design methodologists have successfully used affordances to develop new tools and techniques, the analytical potential of affordance-based design thinking remains largely unexplored. By drilling into the structure of affordance relationships, we defend the utility of affordances in the design process and for design reasoning.

Bounding the design ecosystem

An ecosystem is a unit of analysis consisting of a community of organisms and the environment in which they operate. When examining the design ecosystem, the design methodologist can choose to set their system boundary to be as narrow or broad as suits their research purposes.

Narrowly, we might focus on a particular engineer or designer engaged in a particular subtask of design such as ideation or optimization, or we might broaden our scope to include individuals involved in design, design methodology, manufacturing, use, disposal, finance, marketing, maintenance and other critical or auxiliary roles in the process of creating and using new products and systems.

While in some cases it makes sense to adopt a narrower approach and isolate design as a particular subprocess in a problem-solving system (*e.g.,* (Ulrich, 2011)), adopting the broad perspective allows us to examine the structure of the problem-solving system as a whole. Embracing the embeddedness of the designer within this broader system allows us to more easily understand and map the relationships on which the designer depends, to understand how these other parts of the problem-solving system work together in practice, and to empower design methodologists with tools to identify and act on opportunities to improve the ability of the design ecosystem to solve pressing problems.

The broad perspective further suggests the ability of design researchers and methodologists to move between self-aware analysis of their own work as the design of design methods, to analysis of the process of designing and redesigning of artifacts, to the manufacture, use, and disposal of those artifacts – all while maintaining the same theoretical foundation. This is possible because the realist philosophy of ecological psychology guides the researcher to analyze the resources and conditions that allow individuals to perform goal-oriented activity.

Perceptual realism

The study of how organisms are able to achieve their goals in real environments is the domain of ecological psychology, and one of its basic tenets is the “realist” perspective (Shaw *et al.*, 1982). Realism is the notion underpinning science that there is a real world that we collectively inhabit and individually perceive, and ecological psychology has grappled with the question of how that process of perception occurs from the perspective of the perceiver.

In this fashion, ecological psychology is a fundamentally phenomenological approach. Instead of studying the physical properties of eyes and nerves and the visual cortex, ecological psychologists study the first-person, embodied process of perceiving the world while engaged in the day-to-day business of achieving goals. Ecological realism contends that what is real for the individual is the stuff that she can immediately see and touch and manipulate and use, because it is through this kind of interaction with one’s environment that all meaningful action occurs.

In general, ecological psychologists eschew the use (but do not necessarily reject the validity) of theories based on the cognitive manipulation of mental models, focusing instead on identifying what physical sources of information are available in the environment to indicate the presence of affordances. In doing so, researchers develop an understanding of the necessary and sufficient conditions that must hold for those affordances to exist.

When it comes to design, the realist perspective urges us to focus on the embodied processes of doing design and of creating design tools. Any instance of commercial artifact creation occurs because a network of design methodologists, designers, marketers, manufacturing workers, users, and others have engaged in the day-to-day process of goal-oriented action guided by their perceptions of and interactions with their surroundings. The tools of ecology and ecological psychology allow us to study and design tools for each of these roles with the same set of foundational models and analytical tools.

An ecosystem of technologies

Artifacts, tools, and representational systems also inhabit a kind of technological ecosystem. Because they are products of and components in a larger technological ecosystem, artifacts are not used and cannot be designed in a vacuum. Just as the existence of cars implies the existence of drivers and roads, the existence of roads likewise implies the existence of construction equipment and crews and civil engineers. However, even though this web of technological codependency is a fundamental condition of modern human existence, it lacks a role in traditional engineering design processes.

Like natural objects and environmental features, artifacts are affordance carriers, and the ecological perspective implies the need to analyze, understand, and design these artifacts not only to provide functionality, but also to be integrated components of their broader ecosystem. Unlike natural objects and features, artifacts are designed and created out of available resources to exhibit desired behaviors – their functions (Houkes and Vermaas, 2010). These functions are in part selected to support users' ability to perform actions that achieve goals (*i.e.,* selected for the affordances they support), and this identification, selection, and realization of physical structures that provide desired functionality is the domain of traditional engineering design. However, function-centric design methods largely focus on the internal behavior of artifacts and do not readily support the environment-centric perspective in an unambiguous fashion (c.f. (Eckert *et al.*, 2011)).

The need for a holistic approach to technology ecosystems has been widely embraced by modern firms, since the design and control of such ecosystems can provide significant competitive advantage. For example, the success of the iPod was due in part to its close integration with external hardware (Mac computers) and software (iTunes) that allowed users to easily acquire music and load it onto the device. Likewise, the success of the nascent all-electric vehicle industry is closely tied with widespread availability of both batteries and battery charging infrastructure.

An ecological approach to design embraces this technological interconnectivity as fundamental to the industrial process. By working to understand the embodied process of using the systems being designed (*e.g.,* through prototyping) and by capturing requirements in affordance terms, designers can describe and design for the social and technological environment in which their artifacts will exist.

Affordance-based reasoning

Brown and Blessing (2005) understand the difference between function- and affordance-based design reasoning as "given a function predict possible devices," versus ``given a device predict possible user actions." We see the reasoning processes for both perspectives as applying in both directions. From the function perspective, devices are designed to perform particular intended behaviors, and designers are thought to reason from functions to behaviors to device structure (Gero and Kannengiesser, 2004) and to recognize functional behaviors in structures (Chandrasekaran and Josephson, 2000; Houkes and Vermaas, 2010). Meanwhile, affordances are form-dependent behavioral possibilities that cannot be fully specified until the structure of the device has been designed. Brown and Blessing's formulation thus questions the validity of an affordance-based design theory by identifying a chicken-and-egg problem: without a device, how can one identify its affordances?

Specifying an affordance (Figure 21) requires an ``irriducible minimum of three logical terms" that include an organism action term (the behavior that may be performed), the physical layout of the ``surfaces and substances" of the environment (the situational resources with which to perform the behavior), and relevant compatibility relationships between the organism and environment (the conditions that constrain whether an organism can in fact perform the behavior in this situation) (Shaw *et al.*, 1982). In the early, problem-definition stages of affordance-based design, designers are seeking to understand which affordances each situation must present to which users and why (Maier and Fadel, 2009a).

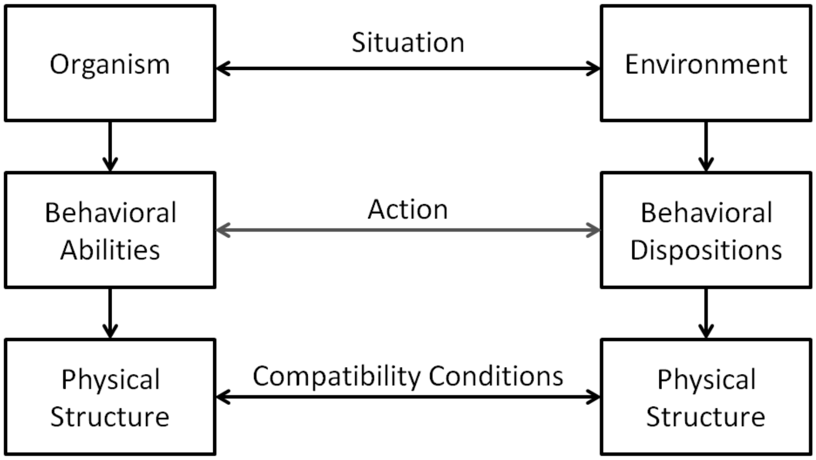

Figure 21: The three terms necessary to specify an affordance (horizontal arrows), and their relationship to the organism and environment.

This affordance-based identification of user needs is not necessarily an identification of fully-specified affordances, which would require knowledge of the design to complete the description of the physical layout of the environment and the environment-organism compatibility conditions. Instead, we argue that early-stage affordance descriptions are necessarily incomplete, perhaps containing only Shaw *et al.*'s organism action term and some rough information about the environment's layout, the organism's abilities, and the environment's behavioral dispositions.

In this approach, early affordance-based design reasoning is no longer about predicting possible actions given a device, but instead about identifying desirable (or undesirable) actions, behaviors, or their outcomes. These actions or outcomes may currently be possible, in that they are already afforded by existing systems (such as driving to work) or they may be impossible, in that they are not afforded by existing systems (putting a man safely on the moon in 1960). In the latter case, without an extant example of a similar system or detailed knowledge of the structure of device-to-be-designed, the desired affordances do not actually exist and therefore cannot be directly perceived. However, it is clear that any successful design should allow performance of the desired action, achievement of the goal, or suppression of undesired behaviors or action possibilities.

It is important to note that, from the realist perspective, affordances are real, existing entities. This means that affordances are not affordance descriptions, they are not comparisons of organism and environment parameters, and they are not abstract concepts which (like functions) are simply waiting to be instantiated in artifacts. An affordance is an actual opportunity for an organism to perform an action, and it does not exist until it is physically possible for the action to be performed!

Therefore, we have to understand affordance-based design as an uncertain, ongoing process of affordance creation in which designers attempt to ensure as best they can that the artifacts and systems they design will, once manufactured, afford use. As the design process progresses past the concept generation phase and into the embodiment and detail design phases, increasingly detailed information merely gives designers an improved ability to predict whether or not the design will provide all the affordances its various users require.

In the following sections we develop a method for exploring the process of affordance creation. In section 6.4 we use the ecological concept of niches to describe systems of affordances. In section 6.5 we discuss how and why to structure descriptions of these systems of affordances in terms of user goals, and present a method for developing such descriptions. In section 6.6 we use this method to describe a generalized design ecosystem, and in doing so demonstrate how the ecological approach unifies the analysis of disparate design methods.

6.4 ECOLOGICAL NICHES

The field of ecology has three ways to analyze relationships between organisms and their environment: by habitat, geographical area, and ecological niche {Alley, 1985 #546}. The first two approaches are spatial in nature, with a species' habitat referring to the range of environmental and ecological conditions that determine places the species could live, and geographical area capturing the area where it does live. However, a species' or organism's ecological niche is defined in terms of behavioral relationships between the organism and its environment, and describes "more to how an animal lives than to where it lives" (Gibson, 1979). Whereas a description of a organism's habitat may describe the type of climate or terrain in which it can be found, a description of its ecological niche catalogs an organism's means of daily coping in terms of "affordance description[s] of the environment" (Alley, 1985).

Particular niches exist because of and are defined relative to the specific types of organisms that can or do inhabit the niche. This is based on the duality of affordances and organism abilities (Chemero, 2003) (sometimes described as "effectivities" (Turvey, 1992)). Therefore, niche specifications describe organisms' "functional[4] relationships with [their] surroundings" in terms of stable "physical-behavioral units" that serve as the "the recurrent settings .. for the everyday activities of persons and groups of persons" (Smith and Varzi, 1999).

Smith and Varzi (1999) identify six features that underly their formal ontology of niches:

(1) A niche occurs in physical space, and consists of objects with physical size, shape, and location.

(2) Niches are complete systems for achieveing particular ends.

(3) Niches have boundaries, in that some objects are part of a niche and some are not.

(4) Objects in a niche may be a part of separate niche or a higher-level niche. A niche itself may be part of a higher level niche.

(5) A niche exists in a location only because of the functional properties of the objects and features in that that location (inasmuch as those properties support its affordances).

(6) A niche's spatial location may overlap with the location of other niches with which it does not share parts such as objects or other features.

Based on these features, we posit that the process of designing, manufacturing, and deploying artifacts for use by particular types of individuals (users) is a process of niche creation and modification and can be usefully analyzed as such. Analyzing the creation of artifacts in terms of niche modification is useful because of the unique features of niches. The features identified by Smith and Varzi (1999) provide a framework of necessary and sufficient conditions for the successful design of technological artifacts (useful things), as well as defining the boundaries of applicability for niche-based analysis of artifacts:

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[4] The use of the word "function" in this instance is not at odds with the affordance-based definition of niches, as it merely denotes the fact that the relationships that define niches involve useful behaviors.

(1) *Deployment:* Changing an organism's niche requires modifying the set of objects in a particular location (*e.g.,*by designing, manufacturing, and deploying an artifact). Successful projects must be able to deliver artifacts to locations in which they can be accessed by users.

(2) *Completeness:* Niches are complete, effective systems for achieving goals (traditionally, survival). Deploying an artifact to an accessible location only matters if it the artifact can be used by an organism (the end-user) as part of their system for achieving particular goals – there cannot be missing elements (batteries-not-included-or-available-for-purchase). Making it possible to achieve a new goal creates a new class of niche.

(3) *Use:* Deploying an artifact only matters if it is put to use by an organism. If two useful artifacts are available, only the one that is used is part of the organism's "realized" niche (Hutchinson, 1978). The useful-but-unused artifact merely contributes to the organism's "fundamental" niche – the set of all possible options for achieving a goal.

(4) *Artifact non-exclusivity*: Artifacts may be part of multiple niches. A particular car is part of its owner's niche, and part of its mechanic's niche, and at one time was part of an assembly-line worker's niche. When that car was part of the worker's niche for passenger-door assembly, it was also part of a higher-order niche for car manufacturing that included the entirety of the worker's niche.

(5) *Affordance modification:* Niche creation or modification can only happen by changing the affordances available to an organism. Opportunities for affordance modification (Figure 21) include altering situational variables such as the organism-environment configuration, the abilities of the user, behavioral dispositions of their environment, or the physical structure of either.

(6) *Spatial non-exclusivity:* A location may support multiple niches, such as a gymnasium providing a niche for both basketball and volleyball players. Deploying artifacts (such as basketball hoops) to a location only modifes niches for the organisms (basketball players) for which the artifact contributes or removes affordances.

Using niche descriptions for artifact design therefore requires information about (1) the organism's environment, (2) the goal for which the niche's affordances are a sufficient solution, (3) the affordances that form the niche, (4) the other niches in which the artifact plays a role, (5) the structure of the artifact's affordances, and (6) other niches that may be present in which the artifact does not play a role.

The opportunity to plan and modify niches is itself part of humanity's niche in general and the designer's in particular. We can begin to understand the process of design in terms of relationships between those who inhabit a niche and those who seek to change it. To understand the relationship between niche inhabitant and niche modifier we must be able to identify what differentiates particular niches (*e.g.,* before and after modification), describe their strucutre, and describe how they come to be altered. Furthermore, tools for identifying, describing, and planning the modification of niches are of particular interest to those who would use such tools – designers themselves.

The technologies that enable a niche-based analysis of design are tools for the systematic analysis of affordances. Affordances are of central importantance because niches are fundamentally sets of affordances, and only include objects, artifacts, and other entities because of the affordances carried by those entities for particular organisms (users). The existing affordance-based design literature provides tools for identifying, cataloging, and realizing affordances of artifacts to be designed, but these tools do not provide guidance for situating those artifacts within larger systems (niches) or for analyzing the role of other affordance-bearing entities in realizng those niches. The two primary developers and proponents of affordance-based design have been (Norman, 2002) and (Maier and Fadel, 2001; Maier and Fadel, 2003; Maier and Fadel, 2009a; Maier and Fadel, 2009b).

Norman (2002) laid the foundation for understanding the relationship between user and artifact in affordance terms, and provides a set of design principles that can help designers ensure that their designs provide and broadcast the existence of high-quality affordances.

Maier and Fadel (2009a; 2009b) expand on Norman's work and provide a systematic approach for the identification, description, and prioritization of a designed artifact's or system's affordances. They catalog affordances in a structured fashion, and provide tools for mapping affordances to physical components. Maier and Fadel (2009b) presents a method for describing an artifact-to-be-designed's affordance structure using design structure matrices (DSMs). They first describe a set of affordance properties that provide the constraints on affordance definitions, including:

complementarity: affordances are interactions between two systems, and must be defined relative to both,

polarity: affordances can be desirable or undesirable.

multiplicity: artifacts and systems can have many affordances.

quality: affordances can have degrees of quality, such that one system may provide a particular type of affordance better or worse than another system

form dependence: affordances are dependent on the structure of the interacting systems.

Maier and Fadel's affordance structures map affordance descriptions to the artifact features and components involved with providing that affordance, and provide tools for documenting the existence of interactions between affordances and between components. These DSMs segregate affordances into desirable and undesirable artifact-artifact affordances (AAAs) and artifact-user affordancs (AUAs). Maier and Fadel present a set of generic affordance categories (Figure 22) to act as a starting point for analysis.

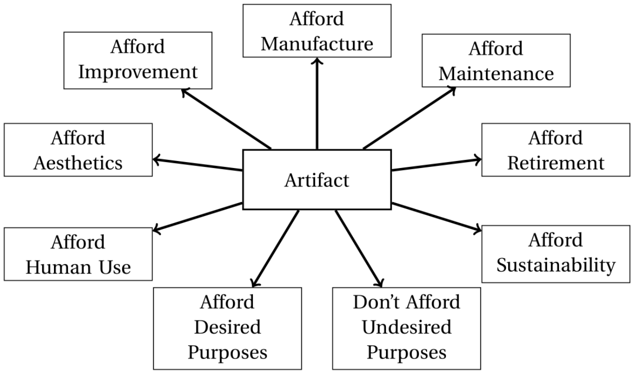

Figure 22: The generic affordance structure template describes the basic categories of affordances that any artifact must provide throughout its lifecycle. (Adapted from (Maier and Fadel, 2009b))

If we generalize the application of affordance-cataloging tools from the analysis of artifacts to be designed to the analysis of preexisting artifacts and other affordance carriers, we can begin to develop a niche-analysis toolkit for design. Our approach to niche analysis builds on the tools of affordance-based design to help design methodologists and design practitioners account for users' social and technological context in a systematic and theory-based fashion. As we mentioned earlier, niche analysis requires the ability to describe the affordances of a variety of resources, including how and why those affordances are used ().

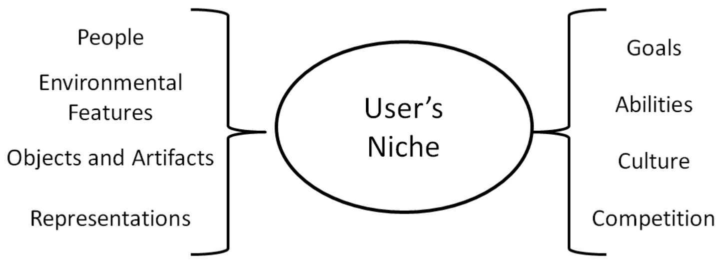

Figure 23: Elements of niche analysis for user-centric design. Users are presented with affordances from a variety of sources, and make use of those affordances in base on their intentions, abilities, and experience.

The affordances available to an individual in a given situation can come from people, environmental features, objects, artifacts, and representations (Gibson, 1979 4; Gero and Kannengiesser, 2012), and their use is driven and constrained by the individual's goal orientation (Scarantino, 2003), abilities (Chemero, 2003), culture (Gaver, 1991), and competition (Alley, 1985).

Much of the criticism of affordance-based methods has revolved around the "infinite" (Brown and Blessing, 2005) number of affordances that each object can possess, and express a need for a means of identifying important or relevant affordances. For niche analysis, the issue is that the affordances of all entities in a situation are candidates for inclusion in the niche description. While the affordances themselves are the fundamental constrain on niche existence, require a method for guiding the development of niche descriptions to include only relevant affordances and affordance carriers.

In the following section, we posit that principle of niche *completeness* means that niche types and boundaries are broadly determined by the organism's goals, and narrowly determined by the organism's method of achieving those goals (*e.g.,*the particular set of objects, affordances, and actions). These definitional approaches together circumscribe the strategies for niche alteration through design.

6.5 A GOAL-CENTRIC APPROACH

Maier and Fadel (2009a) suggest that "design is the specification of a system structure that does possess certain desired affordances to support certain desired behaviors, but does not possess certain undesired affordances to avoid certain undesired behaviors." However, this definition does not address the reason why certain behaviors are desired of systems, stating only that designers should capture contextual knowledge of the use situation "including everything that will need to be done with the artifact (which leads to everything the artifact needs to afford)" (Maier and Fadel, 2009a).

Action theory suggests that useful things such as natural and artificial objects can be analyzed in terms of plans (Houkes and Vermaas, 2010; Pols, 2012), where a plan is a "set of considered actions" (Houkes and Vermaas, 2010) that may involve manipulations of an object and which can be expected to result in goal achievement. Plans are differentiated at four levels - the goals pursued, the actions performed, and the objects, artifacts, and other equipment used. Because physical things and representational systems are carriers of affordances, altering the equipment available to an individual alters the set of actions that their environment affords, and the ability to perform different actions allows individuals to achieve either new goals or old goals in a different way.

The benefit of an approach defined at the goal level is twofold. The first benefit is that because of *boundedness,* a goal-based definition allows niche boundaries to be extended across the locations, organisms, and processes that make up the artifact lifecycle. The extreme of this approach is defining a niche for end-use in terms of the totality of individuals, processes, and resources that went into its design and development. Focusing on goal achievement presents the design methodologist with an opportunity to fully circumscribe the set of individuals and activities that comprise the design, manufacture, distribution, use, and retirement of artifacts with a single foundational theory. Even though the affordance structure is different for each phase of the artifact life cycle, they can be analyzed according to the principles set forth in the affordance and affordance-based design literature, and the interrelated niches that make up the design process can be untangled and laid bare for further analysis.

The second benefit comes from adopting a definition based on the notion of goals as opposed to behaviors. A goal-based definition is more general than one based on behavior because it anchors action, affordance, and behavior-level requirements to a concept that captures the essence of needs. Best practices in design advocate seeking the root cause of problems, allowing designers to select the right level of abstraction for their problem definitions and avoid over-constraining the solution space (Ulrich, 2011). If designers analyze the end-user's goals independent of any particular artifact-to-be-designed, they can begin the design process with the maximum breadth of solution space, increasing flexibility and delaying costly decisions. Explicitly linking required affordances to high-level goals builds system-level verification and validation opportunities into a design scenario, especially if those goals require execution of a plan involving many behaviors. This can help avoid situations in which individual affordance-level tests (*e.g.,*to determine if a particular low-level action or behavior can be performed) fail to capture behavior that emerges or fails to emerge after system integration.

Goal-level needs specifications are more general than behavior-level requirements because unlike behaviors, goals are purely intentional concepts and therefore more solution-agnostic. It is possible that early-stage design requirements specified at the behavioral level are more likely to act as a cognitive anchor during solution ideation. This is particularly true if the behavioral specifications are linked to the physical structure of existing solutions, such as defining the need for *a more efficient car* when the user's real desire was *a less expensive commute to work*. Developing requirements in terms of goals allows designers to specify constraints on candidate designs with a minimum of information about the form of the solution. For example, the solution to a particular design problem might be a product to be sold, a product-service system, or simply training users to exercise new abilities.

Lastly, goal-level specifications are necessary from the perspective of design-as-niche-modification. Because a niche is the set of affordances that a type of organism uses, modifying those affordances changes the niche. Without a goal-level requirement specification we are left without a means of identifying or comparing niches. If a fundamental niche consists of the variety of ways in which a particular goal can be achieved by a particular type of organism, and a realized niche is the specific set of affordances and affordance carriers used by that organism (Hutchinson, 1978), then Houkes and Vermass' plan-based model of artifact use provides a graduated framework for describing niche alteration (Table 1).

By altering	Realized niche	Fundamental Niche
Goals	Different niche type	Different niche type
Only actions (same goals)	Different niche type	Unaltered
Only artifacts used (same actions, goals)	Different niche type	Unaltered
Actions and artifacts (same goals)	Different niche type	Unaltered

Table 1: Altering different elements of a use-plan results in different types of niche changes

Our approach to a niche-based analysis of design is therefore based on decomposing use scenarios to understand how individuals currently achieve particular goals, followed by an analysis of how and why niche parameters can be altered by designers. While our immediate goal is the development of a framework for understanding the design process, we also recognize the utility of this approach for designers themselves. For a designer, niche analysis represents a structured, holistic means for identifying and describing design opportunities.

The core of our approach involves collecting sufficient information to specify the relevant niches for a particular artifact. Because of *artifact non-exclusivity* and *multiplicity*, artifacts can be part of multiple niches throughout their life-cycle because they provide affordances to multiple types of individuals. Because of *boundedness,* these niches can be identified and evaluated in terms of a single circumscribing niche. For an ecological approach to design to be complete, it is necessary to be able to define this circumscribing niche and account for all sub-niches relevant to the design, creation, and use of the artifact. For designers engaged in the design process, it may only be necessary to consider particular niches, such as end-use or a specific manufacturing process.

Niche definitions should begin by identifying the niche inhabitants, such as an artifact's user or intended type of user. For the analysis of existing artifacts one has the opportunity to directly identify the artifact's users. For the identification of design opportunities, one must specify an intented type of user. Users can be usefully described in both functional and parametric terms. Functional user descriptions focus on the user's behavioral abilities, which determine the affordances available to them in a particular environment. Parametric user descriptions may be affordance-defining ergonomic data like leg length (Warren, 1984) or demographic data such as socioeconomic class, geographical location, and cultural background. As Gibson (1979) noted, social and interpersonal affordances are extremely important for humans, and play a large role in day-to-day goal achievement. Social relationships, attitudes, and expectations may differ significantly between different cultures (Gaver, 1991), which may alter the existence of interpersonal affordances.

Specifying the user's goals determines the type of niche. For design purposes, goals should be described in observer-independent terms about the user's existing or desired situation. Defining goals as minimally as possible without sacrificing specificity will help avoid over-constraining the design space. For a given overall goal there may exist subgoals, and the principle of *artifact non-exclusivity* implies that these goals may be used to define sub-niches.

Available resources and their affordances determine the extent of the user's fundamental niche. These resources include physical artifacts, objects, and environmental features, along with representations such as drawings, writings, and mathematical or computer models. Resources also include social affordances, and therefore other individuals either in the user's immediate environment or who can be interacted with via parts of the user's environment (*e.g.,*via a phone or the internet).

The utilized set of resources and affordances define a user's realized niche, and are a subset of the available resources. Identifying utilized resources and affordances requires knowledge of the user's behavioral patterns in terms of the actions they perform, which can be described in terms of use plans. A complete action specification will capture the initial conditions, resources, affordances, abilities, manipulations, effects, and outcomes involved. A structured understanding of the user's current realized niche allows designers to link gaps in the user experience (Ulrich, 2011) to particular resources, affordances, or portions of a use plan. This helps identify design opportunities that involve modifying the user's realized niche through artifact addition, alteration, or subsitution, and the ability to compare the *quality* of the affordances of candidate design solutions both to other solution candidates and to the resources currently in use.

Finally, any key affordances can be decomposed to understand their parameters, constraints, and opportunities for improvement. Affordance models consist of three types of organism-environment relationships, shown earlier in Figure 21. First is a description of the situation in terms of its physical configuration: where does the individual have to be relative to environmental features to take advantage of the affordance, and how must those environmental features be configured? While a doorknob affords turning, its user must be able to reach it, and the door must already be closed to afford opening. Likewise a designer must be physically present at a computer to manipulate a CAD model, and the computer must be powered on.

Second is a description of the action itself: what abilities does the user need to exercise, and what behavioral dispositions must the environmental feature exhibit when the user acts? To turn the doorknob, the user must be able to create torque, and the knob must turn when that torque is applied. The designer must know how and be physically able to type and use a mouse, and the computer must accept and interpret the input correctly.

Third is a description of physical compatibility conditions that must hold. The doorknob must be of a certain size relative to its user's hand to afford grasping, and the door itself must be sufficiently wide to afford passage. The keyboard and mouse must be appropriately sized to the designer's hands, and the designer must have use of them.

The information generated in this process captures the structure of an existing niche, and provides the foundation for describing design opportunities in ecological terms. Once the initial niche description has been developed designers can discuss the goals of their project in terms of how they might modify the user's niche.

In this section we presented an ecological approach to use-scenario decomposition and analysis in terms of goals and niches for goal achievment. We then proposed how knowledge of niche-based methods allows design methodologists to study design processes in terms of niche alteration, and designers to systematically explore niche alteration strategies. Selection of one of these strategies finalizes the definition of the design opportunity. At this point, the role of the designer is to explore the design space, develop design concepts, and plan their deployment. In the following section, we use our approach to map and describe the basic niches of the design ecosystem.

6.6 DESCRIBING A DESIGN ECOSYSTEM

In this section we describe the structure of a generic artifact design ecosystem in terms of niches. These niche desciptions represent the chain of relationships that make it possible to design, manufacture, and provide affordance-bearing artifacts to a user. We identify overlaps and interdependencies between the niches and discuss the application of our analytical method to each in turn. Analyzing the design ecosystem in this fashion uncovers opportunities to situate, describe, and analyze the use of various design tools by design process participants. The result is a set of parallel frameworks, one describing the design ecosystem itself and one describing the ecosystem of design tools, methods, and processes.

We define our example ecosystem in terms of user-centric design. The design ecosystem is a coherent, bounded, high-level niche for designing and delivering useful artifacts to a user or class of users. The process of designing, delivering, and using artifacts involves one or more individuals performing a set of activities within the niche, beginning with the identification of a design opportunity and ending with the use of a designed artifact by an end-user for the achievement of a particular goal. This final instance of artifact use for goal achievement is what determines the boundary of the design ecosystem. An analogy is that a niche for artifact use includes the niches of the artifact's design ecosystem in the same way that the niche of an apex predator includes the niches of the various lower tiers of the food chain. Without the supporting, upstream niches there would be no artifact or predator.

User-centric design opportunities arise in situations in which an individual experiences a "gap," or difference in what they can do and what they want or need to do (Ulrich, 2011), and the design ecosystem structures itself around addressing this gap. The goal of the participants in a user-centric design process is to identify gaps in user experiences that represent viable design opportunities, and to develop designs and specifications for artifacts to fill those gaps. The goal of the participants in a production process is to manufacture and distribute the artifacts that meet the designer's specifications. Lastly, the goal of design theorists and methodologists is to identify gaps in the designer's ability to perform the design process, and to develop tools and techniques to address them.

Each of these sub-goals defines a type of niche within the design ecosystem (Figure 24). Each arrow in the diagram represents a dependency, in that one niche provides or shares affordance-bearing resources with the other. The niche for artifact end-use depends on the creation and acquisition of artifacts (arrow 1). Artifact creation depends on the provision of artifact design specifications (arrow 2). Artifact design depends on design tools (arrow 3), knowledge about the end-user (arrow 4), and capabilities of production systems (arrow 7). Design theorists and methodologists must be able to study and understand each of the niches (arrows 5, 6, and 8) to develop effective tools for designers.

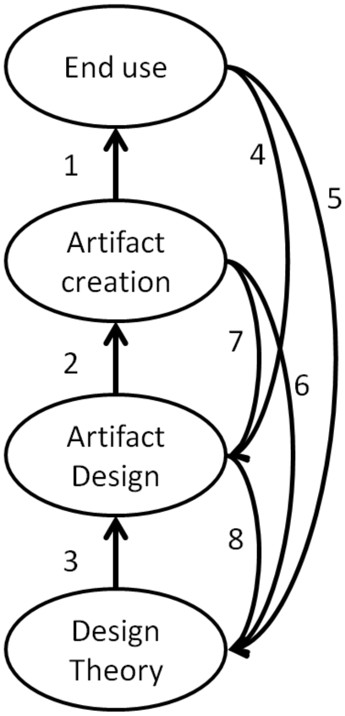

Figure 24: End use, artifact creation, artifact design, and design theory are interconnected and interdependent elements of the design ecosystem.

Throughout the remainder of this section we present a description of each niche type developed in accordance with the method presented in the previous section. We demonstrate the process of identifying niches, the niche's inhabitants, the types of goals they pursue, their available resources, and their available affordances. For each portion of the process in each niche we discuss common activities, analyses or design tools and the role they play from the overall ecological perspective.

6.6.1 END USE

Inhabitants

End-users are differentiated in terms of geographical, cultural, and socioeconomic background. These factors determine much about their niches, their environment, their goals, access to resources, and abilities. Designers will target different types of users based factors including the design team's goals, industry, and approach to geographical and economic market segmentation. For example, potential end-users in the developed world and those in the developing world are likely to have significantly different environmental, cultural, economic, and social backgrounds. While a representative bicycle user in the

United States might be a recreational user, one in the developing world is likely to be a commuter or commercial user.

Goals

Goals are desired or intended states of affairs and can be defined at many levels of abstraction. For example, a recreational cyclist's goals might be described in terms of overall level fitness achieved, specific routes to travel, preferred operational regimes, or amateur race results. Gaps at the goal level include the inability of an individual to achieve a goal or experiencing difficulty doing so with existing resources. The owner of a road bicycle will be unable to ride rough trails. The owner of a poorly designed or manufactured bicycle may experience frequent mechanical problems. Design opportunities at the goal level include making it possible for different users to achieve a goal or by making it possible for the original type of user to achieve a new type of goal. Adaptive cycles allow individuals without use of their legs to participate in cycling sports, while integrated telemetry systems allow racers to target specific biomechanical goals in training.

From the ecological perspective, the appropriate level of abstraction for goal-based requirements is one that defines an objective, observable outcome of user behavior that can be actively incorporated into design processes. As requirements, goals should also be described in a way that is useful for verification and validation processes. Furthermore, it is important that goal descriptions be robust and generalize well across the individuals in a target user group. This means that a good goal description has a degree of built-in awareness of the natural variability in available resources and abilities of the intended user base.

Tools for requirements elicitation and definition such as the "five whys" of the Toyota method are useful for identifying the appropriate level of abstraction for a particular design situation. For example, many recreational bicyclists in the developed world have competition performance as their goal. This is a sufficiently general description because this type of user will participate in some kind of training regimen involving specific types of equipment (bicycle, helmet, shoes, clothing, performance monitors, etc.) and types of use patterns (training rides, race participation). While each user's particular goals may vary by degree, it is possible to model their individual degree of success with straightforward performance metrics (*e.g.,*biomechanical output, aerodynamic drag, or success in competition). This allows designers to compare different design opportunities and different solution candidates in terms of their ability to support the user's goal-achievement process.

Meanwhile, a developing world bicycle user may have an entirely different set of goals because they use their bicycle to operate a business. An appropriate goal description in this case might be in terms of freight capacity, reliability, cost of upkeep, or profit. Even though the underlying bicycle technology is largely the same and affords the same set of actions, analyzing the commercial user's situation will yield an entirely different set of success metrics, relevant resources, and required affordance relationships.

Resources

The set of resources and affordances available to a user in a particular situation determines what actions they can perform and what goals they can achieve. Resources include artifacts, objects, environmental features, and other people. Resources that are actively used determine which use-niches are realized, and when a user acquires a new resource such as a newly designed artifact there is a chance for niche modification to occur. Targeted niche modification through provision of appropriate, useful artifact types is the fundamental goal of user- and use-centric design. However, merely providing artifacts is insufficient for successful niche modification. Instead there are three possible outcomes of introducing a new artifact to a situation: creation of new types of action opportunities, replacement of existing resources, or failure to be adopted by the user.

An artifact creates new types of action opportunities when it provides new affordances, such as manipulation or effect opportunities (Pols, 2012). Action opportunities may only be new relative to the user's situation, or may be the result of technological innovation. For example, acquiring a first bicycle gives a user the opportunity to learn to ride a bike. Likewise, transplanting technologies from one culture, situation, or geographical location to another can be a viable strategy for expanding access to markets. On the other hand, the very first bicycle, automobile, and home computer all represent situations where every new user of a system was presented with entirely new categories of affordances. Realizing new types of afforded actions is an important aspect of many design projects, especially those that involve the development of innovative technologies.

If the user acquires an artifact and the artifact is used to achieve a particular goal then the artifact becomes part of the use-niche for that goal, such as purchasing a bicycle and using it to ride to work. Replacing existing solutions means supplanting existing means for achieving a goal, such as riding the new bike to work instead of driving the car.

When artifacts are made available and yet are not used then they fail to modify any user niches. This may occur if superior or otherwise preferred options already exist, or if the artifacts are too expensive, or if they are simply poor designs. Artifacts can likewise fall out of use and no longer be part of a realized use-niche. Both of these outcomes are common consequences of poor martechnological obsolecence

Though traditionally the domain of marketing and business strategists, understanding the channels by which potential end-users can acquire products is an important element of an ecological approach to design. These channels are important from an ecological perspective because they are part of the user's overall niche and circumscribe the ways in which niche modification can occur. These channels often rely on individuals to actively seek out opportunities to acquire the designed artifact, and therefore it is generally impossible to precisely know by whom, in what situations, or even if the designed artifacts will actually be used. This means that the individuals evaluated by designers in the early stages of design (arrow 4) are usually at best a small subset of those who later acquire the artifact. It is in part for this reason that diligent market research, customer discovery, and robust early stage design processes are critical for the success of a design project.

Affordances

Affordances are user-relative action opportunities. These opportunities can be desirable or undesirable, and the goal of design processes is to support the former and suppress the latter (Maier and Fadel, 2009a). Identifying particular affordances requires specifying the physical context in which the affordance exists, relevant user abilities and artifact behavioral dispositions, and the structural relationship that determines if the user and artifact are compatible.

Physical context means specifying the type and arrangement of available resources necessary for a particular action, such as bicycle riding requiring a bicycle, helmet, and hard surface like a road or path on which to ride. Designers can indirectly support or suppress the affordances of an artifact by providing or removing supporting resources. For example, while a bicycle can be ridden on the street, providing a dedicated bicycle path improves the rideability of a bicycle in a certain location. Identifying supporting resources for particular affordances is a means of mapping technological interdependency between artifacts and guides designers to consider a broader range of design options. Many technologies require the presence of supporting resources, such as electricity, internet access, or well-maintained roads.

User abilities or effectivities are defined relative to an artifact and consist of the actions the user can perform by virtue of the artifact's behavioral dispositions (Chemero, 2003). For example, an individual must have the ability to push before they can open a door, or walk before they can climb stairs. Identifying the abilities of a target group of end users constrains the type of artifacts that will be suitable solutions. The field of universal design guides designers in how to account for variations in user abilities and apply this knowledge to the design of artifacts and environments (Iwarsson and Ståhl, 2003).

Lastly, abilities and affordances exist because of fundamental structural compatibility between user and environment. For example, the classic studies of stair-climbing parameterized user's legs and types of stairs to determine the range of viable and optimal riser:leg ratios for stair climbability (Warren, 1984). Other studies have parameterized affordances for passing through doorways and driving vehicles, and suggest generalized parametirc approaches can be used to describe the existence conditions of any affordances (Shaw *et al.*, 1995).

6.6.2 ARTIFACT CREATION

Niche inhabitants

At this point the users we discuss are not end-users of the artifact, but are instead users of the representations, raw materials, intermediate components, assemblies, and supporting equipment that make the creation and provision of the artifact possible. Depending on the type and volume of artifact to be created, the artifact creation process can involve industrial engineers, factory managers, assembly line workers, and skilled laborers amongst others.

Inhabitant Goals

From an end-use perspective manufacturing systems exist to create affordance-bearing artifacts. The collective goal of the individuals in a particular manufacturing system is produce artifacts in accordance with the specification provided by the designers (Arrow 2). Likewise, the capabilities of the manufacturing system constrain the solution space in which designers are able to operate (Arrow 7). Design tools such as concurrent engineering and design for manufacturability provide designers and industrial engineers with tools to help ensure compatibility between design specifications and manufacturing capabilities. Within the manufacturing system, workers will fill different roles and pursue subgoals related to their portion of the manufacturing process. Oftentimes, an individual worker's goals will involve providing downstream workers with resources such as finished parts or subassemblies.

Resources

The physical resources needed for manufacturing artifacts include the design specification, raw materials, tools, machines, and energy. A manufacturing niche must include affordances for acquiring and using each of these elements. If any critical elements are not available then the manufacturing system is unable to create artifacts.

A design specification is the endpoint of the design process and is an affordance-bearing artifact used by artifact creators. The design specification should support the selection, organization, analysis, and execution of manufacturing processes. Inputs to a manufacturing process may include preassembled subsystems, components, chemicals, or bulk materials. Tools and machines should afford their operators the ability to transform appropriate raw materials and other inputs into desired outputs.

Affordances

The design specification is an affordance-bearing entitiy whose quality is important for artifact creators. The quality of a specification's affordances has to do with the ease with which artifact creators can translate its contents into effective actions. For master machinists, this may be as simple as performing proper geometric dimensioning and tolerancing, while for unskilled workers it may be necessary to provide or translate specifications into step-by-step procedures.

The ability to transform raw materials into finished products depends on fulfilling a set of physical compatibility conditions between each of the worker, their equipment, and their raw materials. For example, to produce a CNC-milled component from a billet aluminum workpiece and 3-axis mill, a worker must be able to set up the workpiece and machine, program the machine, run the program, and remove the finished component. Likewise, the workpiece must be able to fit inside the machine, the machine must accept an appropriate cutting tool, and the program must specify an operational sequence and cutting regime that respects the physical limitations of tool-workpiece interactions (rotational speed, cutting depth, cutting speed, etc.). Each of these compatibility conditions can be expressed in terms of ratios of worker, workpiece, and machine parameters.

Methods of continuous improvement guide the modification of manufacturing environments and processes to improve their usability. Tools such as Lean and Six Sigma help industrial engineers optimize resource use by guiding the selection and configuration of environmental features such as equipment, workspaces, tools, indicators, communication systems, and documentation to reduce waste and improve quality (Pavnaskar *et al.*, 2003; Pyzdek and Keller, 2003). For example, a system redesigned according to Lean principles might provide an assembly worker with exactly the right number of parts needed for a process affords the worker the ability to verify that they have performed all required assembly tasks. Likewise, the principles of poka-yoke (mistake proofing) make it a goal of the design team to create systems that do not afford opportunities for improper use.

6.6.3 DESIGNERS

Niche inhabitants

The individuals that occupy the niches for artifact design are those responsible for identifying a design opportunity, designing a solution, creating a specification, and providing the specification to manufacturers. According to traditional design theory the design opportunity is a chance to transform an initial or existing situation into a final or “preferred” situation for a particular class of end-user. Ulrich (2011) describes problem identification as beginning with someone “sensing a gap” between existing and preferred situations which might be bridged by the creation of some artifact or system. For example, design or market researchers are often responsible for identifying viable design opportunities by observing or interviewing groups of potential end-users (arrow 4). Industrial designers and design engineers then use a model of the design opportunity to develop an artifact specification and provide it to artifact creators (arrow 2).

Inhabitant Goals

The goals of researchers and designers include identifying design opportunities; creating a problem specification; creating design concepts through ideation, optimization, and refinement; and providing detailed final designs in the form of drawings and specifications (Pahl and Beitz, 1996). The goal of the participants in the problem identification and product planning process is to identify a target user group and understand their goals, abilities, and relationship with their environment. This information allows researchers to build a picture of the end-user's existing situation, identify what is undesirable about the situation, and identify what a preferable situation might look like. The goal of designers and engineers is to translate knowledge about the end user and their situation into design specifications.

Resources

Design resources include design processes and representational systems developed by design theorists and methodologists (arrow 3), access to target demographics (arrow 4), communication with manufacturers (arrow 7), design software, optimization algorithms, and prototypes among others. Much like the way in which a well-designed manufacturing process reduces wasted effort on the part of workers, systematic research and design tools can streamline the design process and reduce wasted effort.

The process of problem identification may be systematic or unstructured, with systematic tools including (but not limited to) market research, interviews, observation, and business model analysis (Pahl and Beitz, 1996). Some tools may require access to supporting resources like databases. For example, market segmentation algorithms fit mathematical models to demographic and product data in an effort to predict which products or features are most attractive to which individuals. Identifying specific groups of potential end-users allows researchers and designers to focus further problem definition activities, including the identification, clarification, and classification of user goals, abilities, and resources. Moreover, establishing a relationship with a population of potential users allows designers to gather information and test prototype solutions throughout the design process.

Explicit information about user goals affords the planners an opportunity to decide if they want to develop systems that will support existing goals or allow the achievement of new goals. Likewise, information about abilities affords planners and designers a means of understanding the behavioral limitations of the end-users. Lastly, information about the end-user's relationship with their environment allows planners to understand the affordances found in the user's niche and therefore what actions are already available. Knowledge of existing affordances affords planners and then designers the opportunity to explore design candidates that support, suppress, eliminate, or replace them during the concept generation phase of the design process.

Affordances

Interacting with actual users, their environments, and use situations affords researchers the opportunity to gather low-level information about specific user types or groups. User interviews and observation are two traditional tools that allow researchers to learn about wants, needs, abilities, and behaviors by taking advantage of affordances provided by the interview process. For example, while structured interviews can replicate the kind of data collected by surveys, they additionally afford the interviewer the opportunity to exploit the richness of information afforded by face-to-face communication and the latitude to ask unplanned questions. Interviews therefore afford flexibility, relationship building, and the collection of both structured and unstructured data about how the user defines their goals, abilities, and relationship to their environment and its affordances.

Like interviewing, the goal of observation is to collect structured or unstructured data about a particular type of user or use environment. Observation affords the researcher the opportunity to see how users actually behave in a situation, and and the opportunity for a number of analyses. For example, observed behavior may be different from an interviewee's self-reported behavior such that performing both interviews and observation affords researchers the opportunity to identify meaningful discrepancies that point to design opportunities. More direct approaches involve observing user behvior for inefficiencies, which indicate opportunities to redesign the user's environment to better support the user's activities (Kelley, 2007). Design methodologists have developed tools that help researchers identify design opportunities during observational processes. For example, the tools of lean manufacturing treat the factory as a use environment and workers as users, employing tools like spaghetti charts in conjunction with user observation to identify process waste and opportunities for improvement.

Developing design prototypes and testing them with users involves the creation and provision of example artifacts and affordances, and allows designers to gather information about end-user behavior before the end of the design process. Prototyping affords designers the opportunity to test and refine their hypotheses about user needs and abilities (Leonard and Rayport, 1997; Kelley, 2007).

6.6.4 DESIGN METHODOLOGY

Niche inhabitants

The development of tools to support the design process is the domain of design methodologists in multiple fields, including engineering design, marketing, economics, business, and applied mathematics. This group of individuals includes anyone who creates methods, tools, or processes that describe or help improve designers' ability to identify and address design opportunities.

Inhabitant Goals

Design theorists and methodologists seek to understand how designers actually perform the design process and to identify ways in which the process could be better. Where designers develop artifacts that improve the end-user's ability to achieve their goals, design methodologists do the same for designers. Design theorists develop models of the design process itself, while methodologists develop structured processes and representational systems.

For example, new design tools might afford the representation of new types of data, improve the ability to analyze existing data, or improve decision making processes. The ability to collect new kinds of data might be provided by designing new data collection tools or by identifying new data sources. For example, the rise of the internet, connected devices, and social media has seen researchers develop sophisticated tools and techniques for analyzing and exploiting patterns found in advertising, search, and social media data.

Resources

Design theorists and methodologists use existing theories, representational systems, and methods alongside interactions with and studies of engineers, industrial designers, design and market researchers, product planners, and business decision makers. The niches occupied by design theorists and methodologists include affordances that make it possible for researchers to analyze existing design practices, describe and codify procedures and techniques, create new or modified design methods, and disseminate their knowledge to those who can make use of it. The analysis of existing design practices is the design methodologist's equivalent of market research, in which researchers perform structured observation, inquiry, and analysis processes to identify, describe, and categorize the goals, actions, and tools that design practitioners use in their processes. Researchers engaged in this process require environments and tools that afford the collection and analysis of data.

For example, a perennial difficulty facing design methodologists is creating or obtaining access to such environments. In general, engineering design practitioners are engaged in design projects at corporations, who may or may not be willing to allow academics to access their internal data or design processes. Thus, it has not been until recently that researchers have been able to acquire information regarding how professional design practitioners make use of core engineering design concepts (Eckert *et al.*, 2011). The ecological perspective suggests that this difficulty can be mitigated by developing tools or abilities that afford methodologists access to willing professionals or hard data about how they work. For example, teaching students how to go about acquiring access to and making use of professional engineering design contexts involves teaching them how to take advantage of affordances that already exist – e.g., advisors afford introductions to professionals, corporate personnel afford communication and observation. Workshops at recent engineering design conferences have begun this process of procedural knowledge transfer (Summers and Eckert, 2013), and researchers have begun developing online tools for sharing what data they have acquired.

Affordances

Tools for describing and codifying design procedures and techniques consist of representational systems and their documentation, which carry affordances in a fashion similar to that of physical artifacts

(Gero and Kannengiesser, 2012). According to the use-plan model of goal seeking, these systems should at a minimum allow design methodologists to capture information regarding the goals, actions, and tools used by design practitioners. From an ecological perspective these descriptions should also include information regarding the organisms under analysis (e.g., designers and their coworkers, their resources and abilities), the design environment (including features and configurations of particular objects or other tools of interest to the methodologist), and goal-relevant affordances of the environment.

6.7 CONCLUSION

In this chapter we strove to communicate how fully embracing the ecological roots of affordance-based design can empower design methodologists to understand, evaluate, and improve all aspects of the design process with a single coherent theoretical foundation. While the concepts of affordance and function each have relative merits within the design process, we showed how a realist perspective and affordance-based reasoning support the mapping, analysis, and improvement of design processes and methods arcross the artifact life-cycle.

We describe four requirements for an ecological approach to engineering design, and develop an account of the design and use of artifacts in accordance with these requirements.

First, an ecological approach requires a holistic perspective and should support the identification of an integrated design ecosystem. Using the theory of ecological niches and goals, we describe a complete, bounded design ecosystem in terms of the individuals and resources invovled in use-centric design processes. Our approach uses the properties of niches to subdivide the design ecosystem into individual subsystems that together make use-centric design possible. As such, we describe the design ecosystem in terms of the whole, its parts, and their relationships.

Second, an ecological approach implies a commitment to realism, in that our goal is a framework for analyzing real-world systems, phenomena, and interactions. We develop our method in accordance with realism by examining the physical conditions that allow the identification of design opportunities, the development of artifact design specifications, the manufacture of artifacts, and the acquisition and use of those artifacts by end-users.

Third, an ecological approach requires awareness of the interdependence of both individuals and technologies. We describe how the participants in each portion of the design ecosystem interact with each other to achieve their goals, as well as how individual artifacts and other resources represent components of broader systems and patterns of use.

Fourth, the foundation of the ecological approach is the concept of affordances. We adopt affordance theory as our primary analytical approach, and develop our descriptions using its elements. We describe the extension of tools for affordance-based design to the analysis of systems and situations in general, and describe the affordance structure of each portion of the design ecosystem.

Our approach is informed by the action-theoretic analyses of artifact use that developed from early comparisons of function and affordance as foundational concepts for design reasoning. By understanding all individuals involved in the problem-solving process from design through end-use as goal-seeking organisms and actors, design methodologists can use affordance theory to describe the situations, abilities, and constraints that allow the participants in the design ecosystem to successfully manufacture useful artifacts.

The goal of this work is not discredit, discard, or disengage from traditional approaches to engineering design, but instead to work towards a holistic design theory that supports and guides the use and development of effective traditional and contemporary tools and processes. By adopting the ecological perspective, design theorists gain a set of analytical tools capable of contextualizing, analyzing, and improving the use of design theories and methodologies based on an analysis of the participants in use-centric design processes. Likewise, designers are provided with a set of tools for understanding the nature and limitations of artifacts use.

Future work in this field involves a refinement of our model of the design ecosystem and an in-depth exploration of particular situations, tools, and relationships Likewise, individual design methods such as those advocated by engineering design textbooks represent opportunities to analyze the relationships between design process representations, design representations, designers, and users. How are these systems used in the real world, and what is the structure of their affordances? The ecological approach's commitment to realism means that our results should be corroborated through the observation and analysis of actual design processes.

We feel the ecological approach represents a broad opportunity to assess and improve the design ecosystem in general. By integrating with the field of ecology, the tools of design theory and methodology acquire the ability and need to perform a broad class of new analyses. We feel that identifying and performing such analysis will lead to better design theories, improved design methods, and ultimately better design.

7 SUMMARY AND FUTURE WORK

One of the original goals of this research project was to develop formal systems for automated, technology-based design reasoning. However, to move beyond the capabilities of existing design reasoning systems we found we needed transcend the traditional function-component mappings used in the PPIM and other systems. What we sought was an algorithm that allowed the user to define the desired capabilities of a system-to-be-designed in terms of its affordances.

We found significant obstacles to meaningful progress. We found that existing databases of function-based system decompositions (the kind of databases that automated reasoning systems rely on) held incomplete, incompatible, or non-intuitive system descriptions. We found an increasing awareness in the literature of the impossibility of developing unique, repeatable, general-use function decompositions. Lastly, we found that the function and affordance literature did not address the use of both concepts in conjunction with each other.

Given these obstacles, we decided to focus on the combined use of function and affordance. Our reasoning was that if there is a meaningful way to automate the process of reasoning about technology and technology change, it would need to be built on a foundation that recognized the breadth of complexity of the *technology* concept.

Our research strategy centered around developing a high-level framework to unite the analysis of design methodology, design practice, and artifact use. We approached the topic from the point of view of analyzing *technology* and *useful things*. Resarchers in the fields of design theory, design methodology, and philosophy of technology have all noted that the prevailing, function-based ontologies are unable to describe the fundamental nature of these two concepts, leading to difficulties in both theory development and design practice. Meanwhile, other researchers have demonstrated the ability to use affordance-based ontologies to address some blind spots of function-based methods. Our goal was therefore to integrate function- and affordance-based approaches to design in a way that retained the strengths of the traditional, function-based systems while gaining the additional descriptive powers of the affordance-based approach.

In chapter 3 we began our investigation of the nature of useful things through an examination of techniques for design for technology change. We identified affordance theory as an alterantive approach to technology, and justified its use in extending the PPIM ontology using the technology theory of Heidegger.

In chapter 4 we sought to fill in conceptual gaps identified in chapter 3. In the process of extending the PPIM with affordances, we we found the literature lacked a sufficient analysis of the relationship between the concepts of function and affordance. We used a combination of advances in function theory and action theory to combine the two concepts into a single theoretical framework.

In chapter 5 we further developed our approach to the integration of function and affordance by presenting a representational hierarchy and design methodology using an affordance-based approach to early-stage design and an industry-standard function-based design method. We demonstrated the process for linking high-level affordance information with low-level function information in a practical design environment.

In chapter 6 we explored the implications of an affordance-based perspective by reflecting on affordance theory's origins in ecology theory. We presented an 'ecological' approach to design theory that demonstrates the existence and importance of the totality of affordance relationships necessary for the creation of useful things.

7.1 RESEARCH CONTRIBUTIONS

The primary contribution of this research has been the development of an integrated ontology for describing technological systems with both functions and affordances. We presented a holistic approach to the analysis and design of technological systems. We developed a representational hierarchy for describing use scenarios and user needs, and used it to highlight the structural relationships between functions, affordances, and their representations and descriptions. We used this hierarchy to integrate a representative function-based design process with a representative affordance-based design process, and discussed the utility of this integrated approach for early-stage design. Lastly, we explored the ramifications of fully embracing a Gibsonian ecological perspective, and demonstrated how such an approach is able to address the entirety of the design ecosystem.

The philosophical foundation of this research is its approach to technology and useful things. We identified two approaches to the nature of technology: one reductionist, one not. The dominant, reductionist approach stems from the tradition of analytical philosophy, is based on the concept of function, and focuses on capturing the utility of manufactured goods and systems. Such an approach is applicable primarily to systems that perform transformational, input-output style operations on matter, energy, and information. As such, function-based approaches to technology require the designer to describe systems in input-output terms, biasing design efforts towards solutions that lend themselves to such descriptions.

The other approach is in many respects anti-reductionist in nature and is exemplified by Heidegger's phenomenological dissection of technological artifacts (Heidegger, 1977) and their "equipmental" role in everyday life (Heidegger, 1962). This work uses Heidegger's perpsective to guide the analysis of relationships between elements of sociotechnical systems. We discuss the need for a design theory, design methods, and design tools that explicitly account for the relationships between all varieties of useful things, users, and the purposes to which those useful things are put.

Using function, affordance theory, and action theory to glue the two together, we presented a synthesis of these two approaches to technology. This synthesis provides a framework for capturing requirements, guiding early stage design processes, and analysing arbitrary portions of design ecosystems.

We presented a model of user needs based on goal achievement. Action theory allows us to describe situations in which individuals seek to achieve goals, the plans they intend or attempt to execute, and the affordances and functions that contribute to the process. These descriptions help drive early-stage engineering design processes by providing a schema for the deconstruction of use cases into their constituent parts, including elements that do not involve the artifact that is being designed. This approach allows designers to capture contextual information that allows the systematic application of function-based approaches where and when they are most appropriate. This frees designers from a one-size-fits-all relationship with function based design methods.

We identified similarities between function- and affordance-based methods in the context of action theory. This allows designers retain the benefits of function-based tools (widespread acceptance, software support, efficiency for certain problems) while also gaining the benefits of affordance-based tools (theoretical foundation, technology model, descriptive power). We demonstrated a way in which affordance-based reasoning and the ecological perspective can help guide the systematic improvement of existing design processes.

7.2 BROADER IMPACTS

This dissertation provides a framework for the integration of disparate approaches to design theory and methodology. Affordance-based design is a recent addition to design theory, and deserves a central role in the coming decades of research because affordances are fundamental to the creation and use of technology. However, compared to function-based apporaches, affordance theory is as yet incomplete and in need of further development. By integrating the two methods, affordance theory becomes more accessible and useful to design researchers and design practitioners alike.

Furthermore, the high-level integration of ecology and design theories presents the design theory community with a range of new analytical opportunities. With this approach, design theorists are provided with a framework for the practical analysis, improvement, and integration of design processes.

7.3 RECOMMENDATIONS FOR FUTURE WORK

This dissertation represents a first attempt to integrate two very different design theories and their methodologies. Its further development should involve elaboration of its theoretical underpinnings, development of practical tools and methods, and application of its analysis to existing design tools.

Defining and bounding the concepts ‘function’ and ‘affordance’ remains an open problem in philosophy. While most contemporary accounts are action-theoretic approaches, neither the function or affordance theory communities have reached a definitional consensus. This issue is complicated by the fact that the philosophy of technology has received relatively little attention compared to, say, the philosophy of science. As Heidegger stated, “the nature of technology is ambiguous.”

Practical tools for affordance-based design remain few and far between. The role of affordances in engineering design is all but unexplored. We have presented one way in which affordance-based design can be integrated with function-based methods, but only with a single (albeit important) example. Future work should further examine opportunities to adapt well-understood methods to new contexts, as well as opportunities to develop new tools for underserved communities such as those in the developing world.

Lastly, the ecological approach to design suggests the opportunity for a reevaluation of our relationship with design tools and the design methodologist's relationship with the product life cycle. While opportunities exist for analyzing the structure of popular design methods in something of a vacuum, we feel the most important opportunities lie in studying and seeking to improve existing real-world design processes. It is only by analyzing actual, operational systems of design, manufacture, and use that the full benefit of the approach will be realized. Future work should include in-situ studies of the affordance structure of various design and manufacturing contexts.

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