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INCORPORATING AFFORDANCES INTO PRODUCT ARCHITECTURE: METHODOLOGY AND CASE STUDY

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ABSTRACT

The intention of this paper is to review the Function-Task-Interaction methodology and tools, which have been developed to link product functions and users' tasks and to incorporate the concept of product affordances in product architecture development. This paper also aims to present the results of two investigations. The first was field research conducted with end users to assess their mental models of specific product architecture and related functions; the second was an investigation conducted with design experts from a global manufacturer of mobile communications products. Finally, this paper strives to expand the proposed methodology by introducing a new set of questions and a user-centric vocabulary for representing aspects of user-product interaction in Functional Modeling. The authors argue for the development of a controlled vocabulary to describe and label affordances.

Keywords*: affordance, product architecture, design structure matrix, product interaction and user requirements.*

1. INTRODUCTION

Every product architecture has a purpose, whether it comes from a product-centric or user-centric view. From a product-centric view, product architecture plays a major role during early stages of design in understanding, conceptualizing, and defining the tradeoffs between functions and implementation options. Functional modeling methods, for example, allow developers to explore functions by decomposing product behavior and refining the relationships between functions and product parts. From a user-centric view, the emphasis is on the interaction between the users and the product architecture. This view provides understanding of how users build close relationships with products and how these relationships can be controlled when developers focus their attention on tasks as understood by users. Each view, however, has its weaknesses.

A major weakness of the product-centric view is that users' requirements often are not entirely addressed. As a result, new designs or redesigns may or may not fulfill users' concerns that are crucial to product acceptance in terms of usability and/or visual consistency. Additionally, the lack of appropriate notation to address user-product relationships in product architecture limits the breadth of this view. A major weakness in the user-centric view is the difficulty of translating the output of user research efforts into actionable design specifications for developers. There is a need to better integrate this understanding into the product architecture process; hence, the authors propose the use of task analysis combined with a structured approach, to be known as the Function-Task-Interaction method.

The Function-Task-Interaction method [1] identifies users' issues and explores options for addressing these issues in a manner that aligns with the technical functions of the product. This approach allows developers to look beyond the functionality of new product designs to their larger impact as products interact with end users. The leading hypothesis in this work proposes that improvement in product architecture decisions can be achieved by merging functional oriented and affordance oriented thinking. The method defines a new approach to using the affordance concept during product architecture by helping define the relationships established between the product and the user during product use.

The remainder of this paper focuses on describing and validating the method described. The background section covers the evolution of relationships between user requirements and task analysis, as well as the derivation of product knowledge from functional modeling approaches. Section 3 revisits and presents refinements on the Function-Task-Interaction method and addresses the issue of applying user-product knowledge. In section 4, a case study focuses on the

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validation of that method with analysis and observations on two investigations. The first investigation focuses on the tasks users perform and more importantly on how they perceive product architecture and affordance levels. The second investigation focuses on the use of the methodology by design experts from industry.

2. BACKGROUND AND RESEARCH PERSPECTIVES

This section provides a survey on two research areas: task analysis and functional modeling. Each of these areas could provide enough material for an entire survey paper but, unlike traditional survey papers, this paper does not attempt to provide a comprehensive review of a field of research from its inception to the present. Rather, this paper aims to touch on a representative selection of recent developments in these influential technical areas, to provide a perspective into the challenges emerging from expanding fields, and to discuss the research opportunities and unfilled needs for product development tools.

2.1 Task Analysis

Task analysis has long been used as an essential step to incorporating users' requirements into system design [2]. Diaper in [3] described task analysis as "potentially the most powerful method (…) at all stages of system development, from early requirements specification through to final system evaluation."

In task analysis, a task is what someone does to achieve a goal or a specific need, such as taking a picture, cooking a special dish, and writing a report. Tasks can be broken down into hierarchical descriptions with several levels of abstraction, from general tasks to specific subtasks. These subtasks may include operations users perform almost automatically. The term "Task Analysis" refers to a number of roles required to manage and process task information, including data collection, description, assessment, simulation, and requirement evaluation. A handful of established task analysis techniques help developers to structure the information collected into a systematic format for later analyses. Among the many techniques, the Hierarchical Task Analysis method is preferred for this research because it is widely accepted and is readily understandable [2].

Hierarchical Task Analysis focuses on the way major tasks are hierarchically divided into plans and subtasks, and the order and situations where these are performed. The start-to-finish task arrangement ensures completeness and is easy to comprehend [4]. The output of this analysis is generally represented textually and diagrammatically to illustrate goal structures and cognitive decision-making activities.

The advantage of representing tasks hierarchically at the early stages of the design process is that it allows developers to concentrate on understanding subtasks without losing the concept of the major task activity. Figure 1 illustrates the task of taking pictures with a digital camera. Note that the process of using a digital camera starts with defining a goal which the user of the system intends to achieve. In that process, there are contextual influences that must take effect prior to product use. Examples of contextual influences include factors that may affect the choice of recording media used (i.e. quality of the weather, scenery, type of event).

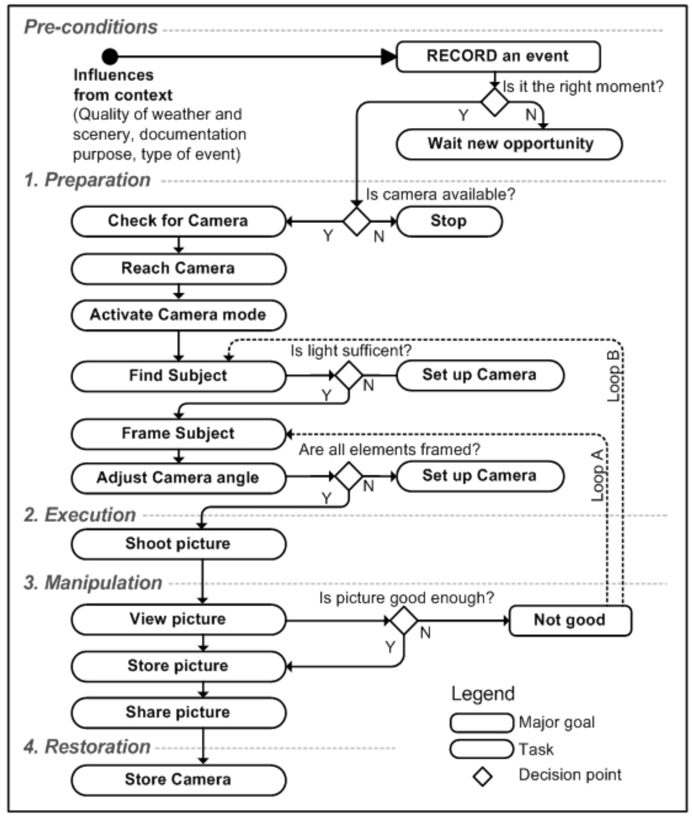

Figure 1. Task flow for taking pictures with a digital camera.

2.1.1 Perspective on Task Analysis Tools

Hierarchical task analysis has historically proven to be labor intensive, time consuming, and costly. As a result, much investment has been made to develop computerized task analysis tools. These tools go beyond word processors, drawing packages, and spreadsheets to address the challenge of numbering tasks, keeping plans consistent, and visualizing the hierarchy. Lee [5] compared several of these tools, from ad hoc to commercial applications that allow specifying the descriptions of the task, modeling the task flow, simulating task models, and checking for their logical consistency. While the more advanced tools provided developers with the ability to check the design implications of task models, their increasing sophistication became a disadvantage. The complexities of these models were found to be difficult to understand by people who were not used to such a structured approach [6]. Figure 2 aligns the complexity of computerized models with different task analysis activities.

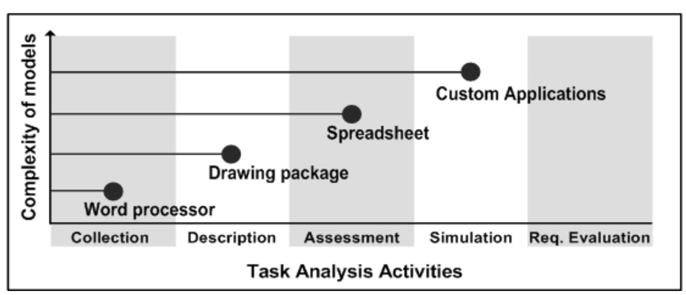

Figure 2. Suitability of tools for task analysis activities [7].

In summary, task analysis tools are useful for the identification and mapping of human input and output

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requirements in the design of devices. The purpose is to show users' tasks, their perceptions of aspects of products, and their interactions with them. This research offers the opportunity to identify the input and output of user processes to understand how to transform that information into useful design knowledge for developers.

2.2 Functional Modeling Analysis

While task analysis approaches are used to describe tasks that users perform, Functional Modeling Analyses in engineering design are used to explain the workings of products by identifying the functions they must perform. Functional Modeling is a critical step in the design process [8][9], helping developers to explain the workings of a product for benchmarking and/or design purposes. The basic idea among functional modeling approaches assumes that a product can be explained by decomposing an overarching function into a set of simpler functions that are organized with logical reasoning. The classic functional modeling methodology following this approach is that of Pahl and Beitz [8]. In their model, functions are decomposed based on the flows of energy, material, and signals.

2.2.1 Perspective on Functional Modeling Methods

Other functional modeling methodologies [10][11][12][13] all attempt to fill in portions of Pahl and Beitz's work, and require in fact answering four questions:

1. **Why was the product designed for in the first place?** The answer to this query explains the purpose(s) of the developer and hence the overall goal of the product.
2. **What is the product supposed to do in order to achieve the overall goal?** The answer to this query explains the sub-functions that the product must perform.
3. **How must different sub-functions of the product be arranged in order to perform the overall function?** The answer to this query explains expected function arrangements within the product, which may suggest input and output flows between functions.
4. **What physical structures must interact in order to realize the functions?** The answer to this query reduces the functional descriptions of a product to its physical elements and explains behaviors of the physical system, as described by Ulrich and Eppinger's four-stage approach towards product architecture generation [14].

More recent functional modeling approaches and formalisms have aimed to respond to these four questions. As a result, terminology describing product function and flows was developed and named Functional Basis [15][16][17]. In Hirtz's work, the function set is broken down into eight categories termed the primary classes and further divisions called the secondary and tertiary levels. Tables 1 and 2 represent the vocabulary used. Functional basis terminology also included some terms for human influence on a device, such as a human energy that turns electricity on and off, or activity to steer or accelerate a vehicle. In the interest of brevity, the authors have omitted other details, which can be found in [16] and [18].

Although functional modeling approaches represent a great advance in engineering design, most methodologies are product-centric and lack mechanisms to identify and organize user-product interactions at the same level of abstraction. Function allocation methods are increasingly needed to ensure users' tasks that should be automated are automated, and that those that require human judgment or are not cost-effective to automate are designed to optimize the human contribution. There is an evident need to substantiate the functional model methodologies by specifying a set of rules in addition to the verb-object format and the flow-heuristics for identification of modules proposed by Stone, Wood and Crawford [19]. The research opportunity is to develop a user-centric terminology and set of questions that can be used to represent user-product interaction aspects and help establish their link to product attributes, such as their functions and necessary affordances. These questions would help identify functions and flows that directly and indirectly interact with intended user groups and are based on previous work around the concept of affordances [1][20].

Table 1. Functional basis function terms

Primary	Branch	Channel	Connect	Control magnitude	Convert	Provision	Signal	Support
Secondary	Separate Distribute	Import Export Transfer Guide	Couple Mix	Actuate Regulate Change Stop	Convert	Store Supply	Sense Indicate Process	Stabilize Secure Position

Table 2. Functional basis flow terms

Primary	Material		Signal	Energy		
Secondary	Human Gas Liquid	Solid Plasma Mixture	Status Control	Human Acoustic Biological Chemical	Electrical Electromagnetic Hydraulic Magnetic	Mechanical Pneumatic Radioactive Thermal

3. LINKING FUNCTIONS AND TASKS

In order to generate designs aligned with human tasks, developers need to determine how functions should be built into the product and what subtasks the product should support. The concept of affordances can serve as a bridge mechanism between functions and user tasks, suggesting desirable product attributes that help users to accomplish their goals and which define directions towards design implementation.

3.1 Incorporating Affordance Thinking

The concept affordance* was first introduced by Gibson [21], in the field of ecological, perceptual psychology. Norman [22] brought the concept of affordance to the field of design and helped to shape the way affordances are understood in human-computer interaction. More recently, Maier and Fadel proposed methods to consider affordances in engineering design by emphasizing satisfaction of user demands (what the artifact should afford) while avoiding unwanted or dangerous features (what the artifact should not afford) [20]. Following their footsteps, Galvao and Sato [1] narrowed down the concept of affordances to describe the linkage between technical functions and users' tasks by introducing the Function-Task-Interaction (FTI) methodology. The FTI method amplifies the product architecture process described by Stone et al. in [23] by adding the following goals: 1) an exploration of users' tasks and subtasks, 2) an identification of affordance requirements, 3) an investigation of user-product interactions and representation

* Gibson coined the term affordance to refer to the actionable properties between the world and an actor. In this paper, the term is consistent with the original definition of affordances, referring to the relationships between technical functions of products and task possibilities of users.

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of affordances in functional modeling, and 4) an exploration of affordance options.

3.2 The Function-Task-Interaction Method

The Function-Task-Interaction Method includes four phases, as illustrated in Figure 3. The first phase in the Function-Task-Interaction methodology is a user and product study that include the collection and organization of information on users' activities and on product architecture. While investigating users, the goal is to increase understanding about them, clearly describe their goals based on hierarchical task analysis, and identify the problems they face with existing products. Tasks are broken down into hierarchical descriptions with several levels of abstraction, from general tasks to specific subtasks. A suite of commercial programs may be used in this phase to capture and organize this information as a conduit to the subsequent analyses. While investigating existing products, the overall functions are defined and decomposed into sub-functions as a means to delineate design problems requiring attention. The decomposition continues until it generates a function structure that organizes top-level and possibly low-level functions. The functional modeling approach is suggested for this phase.

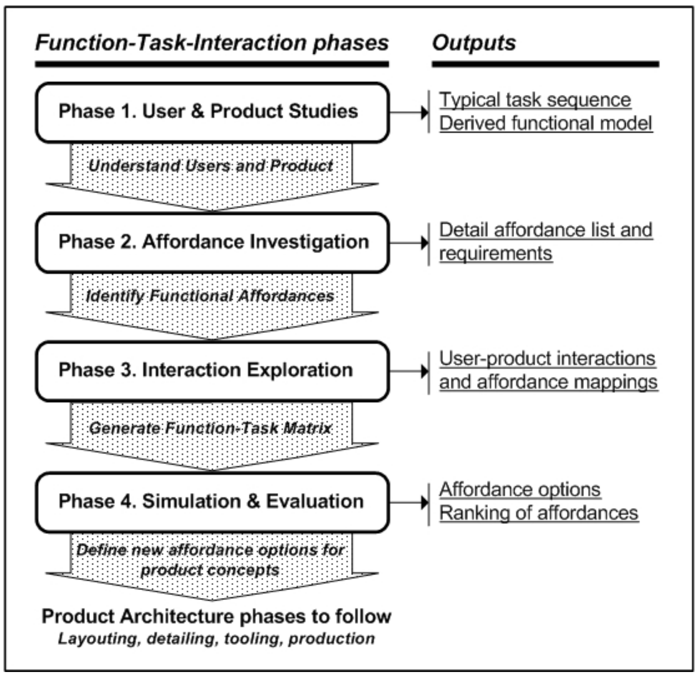

Figure 3. Four-stage approach towards affordance options.

The second phase is the affordance investigation where developers investigate "must have" relationships between the users and the product. Those include both existing and future affordances, depending on the purpose of the project (from incremental improvements to product breakthrough). The process of defining these relationships consists of two steps: 1) understanding user requirements; and 2) interpreting them in terms of required, desirable and undesirable affordances. The output is a list of functional affordances that expands in detail the generic affordance structure proposed in [20]. Functional affordances are high-level relationships that carry a sense of usefulness from the user perspective without necessarily predetermining functions or product attributes. These high-level affordances can be described as "-abilities," such as "read-ability." Together they provide a holistic view of the product, including non-functional requirements. The list allows developers to consider and prioritize "must have" relationships based on the project goals. Figure 4 suggests a generic way to organize these affordances based on the tasks users perform.

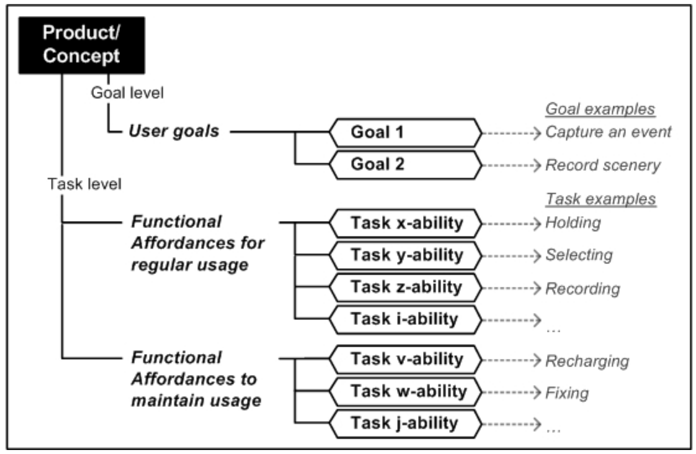

Figure 4. Affordance list.

In the third phase, Interaction Exploration, a variation of the Design Structure Matrix described by Steward [24] relates the users' tasks and the product functions. The strength of this matrix lies in the visualization of the relationships between users' tasks and technical functions. The relationships from functions to tasks specify which product attributes are needed, while the relationships from user tasks to functions specify where affordances can aid users in accessing them. The next subsection provides more details about this matrix.

Finally, in the last phase, or Simulation and Evaluation, developers explore provisional affordance recommendations and options based on the relationships identified in the matrix and the prioritized affordance list.

3.4 The Function-Task-Interaction Matrix

The FTI matrix represents interactions between users' tasks and technical functions. As long as there is some kind of interaction between users and the product being developed, this information remains relevant to the developer, especially for design purposes. The FTI matrix can increase that understanding by identifying which technical functions interact with users, and what types of interactions take place or should be implemented between functions and tasks. This matrix has been refined based on a case study, which will be presented in section 4.

The FTI matrix relates two entities: users' tasks from Hierarchical Task Analysis, and technical functions from functional modeling studies. Figure 5 shows an example of the refined FTI matrix. In the matrix, diamond shapes denote interactions, with filled diamonds for physical interactions (e.g. energy instantiation from human force), and empty diamonds for sensory-cognitive interactions (e.g. information delivery). Note that it is possible for one task to have both types of interaction, and therefore a diamond within another diamond indicates coupled interaction entities (e.g. energy instantiation followed by information exchange). Boxes without diamonds indicate no interaction.

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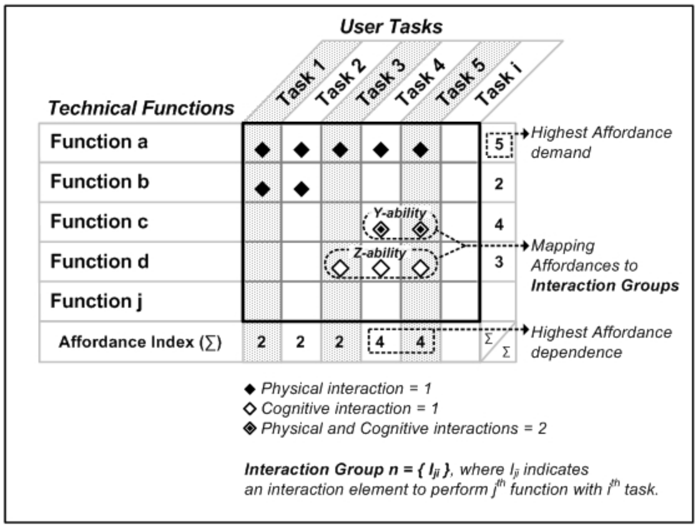

Figure 5. Simplified example of a FTI matrix.

A set of questions help developers identify these interactions, as shown in Figure 6. At the core of these questions are the interaction entities that may or may not be present. Take for example a digital camera, Function (convert signal to image) *demands* **visual information** *from* Task (frame scenery). Conversely, the Task (frame scenery) *depends on* **visual information** *from* Function (convert signal to image).

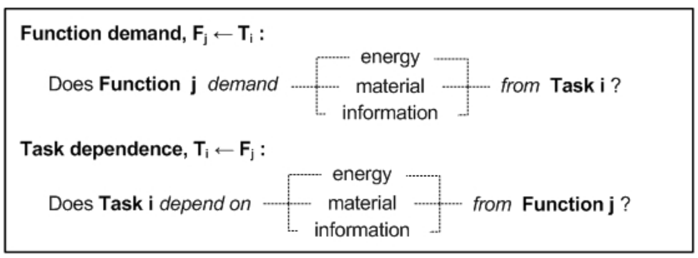

Figure 6. Questions for identifying interaction types on FTI matrix

Another output of the matrix is the groupings of interaction elements that are obtained from each row. These groupings represent functional affordances previously described in the Affordance Investigation phase. Functional model diagrams can also serve as a mechanism to visualize and validate inferences around these affordances. Figure 7 suggests a way to notate and map interaction entities (energy, information and material) and affordances into functional model diagrams.

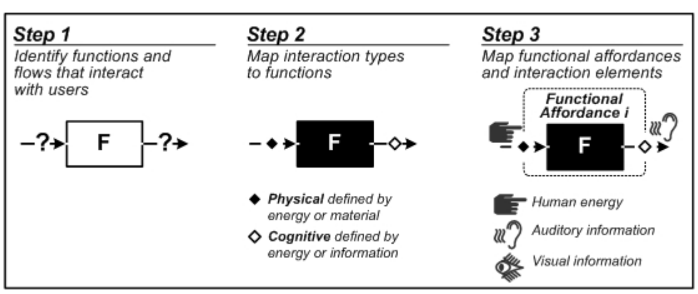

Figure 7. Interaction check-up.

In addition to identifying and defining interactions within an FTI matrix, tasks with higher affordance dependence are determined by vertically summing interaction points from physical and cognitive interactions. By summing points horizontally, developers can determine functions with high affordance demands. The numbers on the bottom of the matrix identify how tasks depend on interaction elements. These numbers on the right and bottom edges of the matrix provide affordance indexes to assist developers in assessing the interaction impact on current and future functions. A greater index number indicates higher demand for affordances, since a larger number of technical functions must conform to a particular task. With greater or fewer numbers of interactions, these indexes reflect the perception of affordance attributes. For instance, five information interactions appearing in one technical function will more strongly suggest the need for affordances. Thus, the number of interactions reflects how easily an affordance can be recognized or how it should be designed.

4. CASE STUDY

The purpose of this case study was to evaluate the appropriateness of the FTI methodology to the early phases of product architecture development. The goals of the study were to verify tasks performed by end users, and to identify and capture product affordances generated from design experts. The study outlines the challenge of validating a design methodology and provides background information necessary to understand the process of analysis.

In order to evaluate the method proposed, two research investigations were conducted. The first investigation included interviews conducted with five end users and a product assessment. The interviews with end users provided input on the task of making a phone call and their understanding of the product architecture and affordances of mobile phones. The device chosen for product assessment was the mobile phone. The choice of this product was based on three criteria: 1) the complexity level of external and internal parts, 2) the product's presence in the market, and 3) the users' familiarity with the product's operation.

The second investigation was conducted with five design experts who currently develop mobile phones for a global manufacturer of communication technologies. These experts were asked to study and assess the information gathered from the end user investigation, and to then simulate affordance options. Figure 8 outlines the overall research approach applied in this case study.

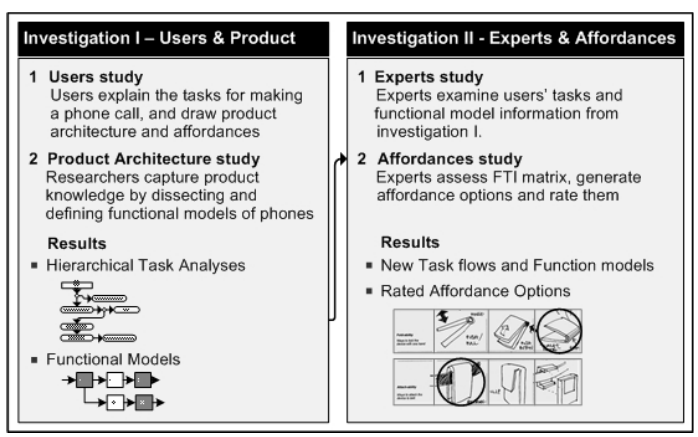

Figure 8. Case study: sequence of studies and results.

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4.1 Investigation I - Users and Product

Mobile phones have become ubiquitous in almost every city; it is believed that the number of mobile subscribers worldwide reached over 2 billion in 2005 [25]. These devices are often overloaded with functions that offer users far more than just the capability to make voice calls. These functions may include: sending text messages, browsing the Internet, playing music files and/or ring tones, organizing schedules, shooting pictures or videos, making payments, playing games, streaming video, and so on. Figure 9 illustrates common product architectures that address and accommodate these functions in many configurations and emphasize several affordances.

Prior to capturing the users' knowledge, two mobile phone models were dissected and documented by the researchers. The "clam type" architecture was chosen for this evaluation and only the primary function of making a voice call was addressed. A functional model diagram was generated based on the functions, product parts, and connections observed. Thirty-one functions were identified and distributed among eight modules. These include: alerting, receiving, viewing, talking, controlling, transmitting, supporting, powering, processing, and hearing. The functions are based on five flows of energy and information: human force, electrical, acoustic, mechanical, and status signal. Appendix I-A illustrates the functional model diagram with functions and related flows.

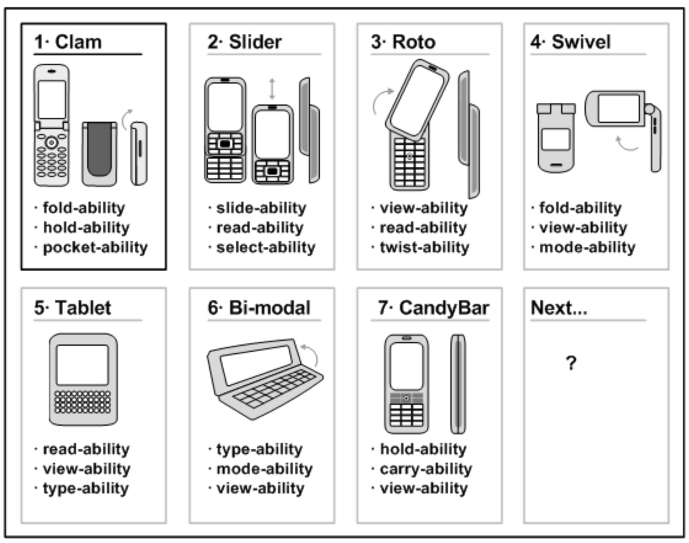


Figure 9. Product architecture of mobile phones.

In order to capture perceived product architecture and affordance attributes, five end users were interviewed and an analysis was defined around their abilities during product interaction and their understanding of mobile phones. Most of the background information about the subjects was collected through semi-structured interviews to determine product-related skills, product knowledge, activities and methods of use. The characteristics of subjects are summarized in Table 3.

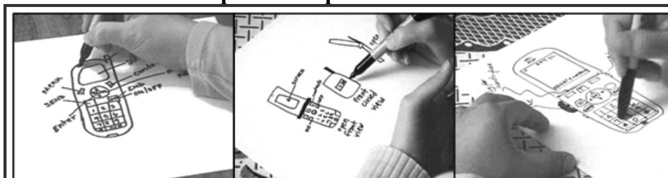
Table 3. Characteristics of subjects.

Gender	Male (1); Female (4)
Age range	21 to 55
Call frequency (%)	Daily (80%), Weekly (20%), Monthly (0%), Yearly (0%)
Product usage (%)	>1 year (20%); >3 years (60%); >5 years (20%)

After the interview, subjects were asked to create a representative sketch of their mobile phone, to identify as many parts as possible, and to describe the purpose of each part. Frequency of occurrence of product parts was identified in drawings of subjects. The results show that subjects used, on average, 83 percent of visible product parts to represent the product. In comparison to previous work on the perceived product architecture of domestic blenders [1] in which users used 63 percent of parts, this is a substantial increase that can be associated with the frequency of use.

In addition to documenting the frequency with which subjects represent product parts, their ability to identify product affordances for product operation was also investigated by prompting questions about the usefulness of each part represented in their drawings. Table 4 shows these findings with user concerns evoked by each part. It also shows the subtasks required for operating each product part and the related functions. The drawings together with the subtask rationale for each part provide descriptions of users' mental models during product interaction. Although this study did not have statistical significance, it demonstrates the range of most important functions and affordances for users.

Table 4. Elements of perceived product architecture.



Parts drawn	Occurrence frequency	Related subtask	Usefulness concerns	Related functions
Screen	1.00	view select push	contrast smudging size	receive E.signal, activate display, convert signal to image
Hinge	0.60	open close lift	robustness resistance	import hand, secure H.E., convert H.E. to M.E., transmit M.E.
Antenna	1.00	pull hold	stability size	import hand, import signal
Speaker	0.80	hear	accessibility size	receive E.signal, convert signal to sound
Microphone	0.80	talk	accessibility size	import S.voice, convert S.voice to E.E., convert E.E. to signal
Front-cover	1.00	view show	style	import hand, export H.E., transmit M.E.
Back-cover	1.00	view show	style	import hand, export H.E., transmit M.E.
On/off button	1.00	press push	accessibility layout	import hand, export H.E., transmit M.E
Key buttons	1.00	press push	accessibility layout	import hand, export H.E., transmit M.E
Dedicated buttons	0.60	press push	accessibility layout	import hand, export H.E., transmit M.E
Plugs	0.60	push insert	accessibility cleanness	store & control E.E.
Processor	0.00	-x-	speed	receive E.signal, activate speaker and display, convert to radio wave, convert signal to sound, convert signal to image, activate vibrator
Average	**0.83** (of visible parts represented)			

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Finally, subjects were also asked to demonstrate how to make a phone call. Using observation movies, researchers studied decisions subjects made as they performed their tasks. Next, hierarchical task analyses were carried down to the subtask level. Based on these observations, it was found that the activity flow for operating a mobile phone is influenced by contextual factors and involves three main goals: preparation, completion, and restoration. These goals and tasks are shown schematically in Figure 10.

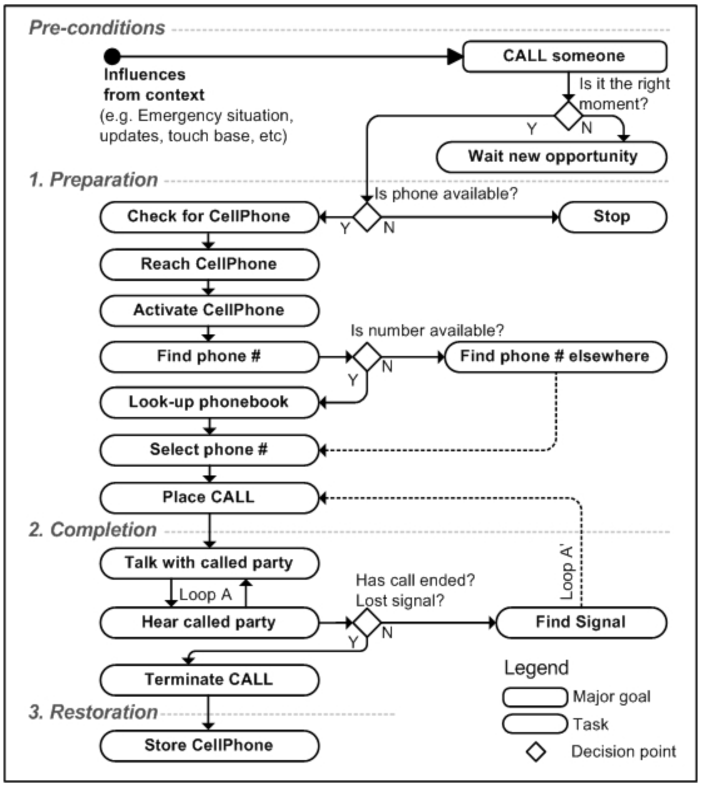

Figure 10. Typical task flow for making a phone call.

With the information obtained from the user and product studies, a Function-Task-Interaction matrix was created to determine potential interactions between current functions and users' tasks (see Appendix I-B). These interactions provide understanding about where functional affordances become relevant for later design phases. Sixty (60) user-product interactions representing twelve (12) functional affordances were found in the clam type mobile phone architecture. The functional affordances identified are: 1) call-ability, 2) converse-ability, 3) view-ability, 4) read-ability 5) hear-ability, 6) hold-ability, 7) fold-ability, 8) attach-ability, 9) detach-ability, 10) select-ability, 11) control-ability, 12) sound-ability. Affordances not identified in the matrix that represent attributes of the device as a whole include: clean-ability; customize-ability, carry-ability, pocket-ability, recharge-ability, memory-ability, assembly-ability, and recycle-ability. These were left outside of the analysis because functional affordances also point to non-functional requirements when originating from users' determinations of desirable and undesirable product aspects, such as customize-ability and smudge-ability respectively. These non-functional requirements may also have cultural and social implications that are outside of the scope of this study.

4.2 Investigation II - Experts and Affordances

Investigation II was conducted with five design experts who currently develop mobile phones professionally. Their experience level averaged five years of designing consumer products. The goals of investigation II were to estimate the accuracy of the task analysis and functional modeling diagrams originated from investigation I and to study creativity in the simulation of affordances. The measures for affordance simulation sought in the study were: 1) *quantity*; 2) *variety*; and 3) *originality*. These are important attributes that define creativity in engineering design [26].

The experts were first shown a stimulus presentation depicting the original task analysis diagram and functional modeling diagram from investigation I. After getting familiarized with the task and function flows, they assessed a FTI matrix to confirm the existence of functional affordances and their correspondent indexes. All five experts agreed with the interactions presented but suggested seven adjustments, accounting for 11.6 percent of the interactions presented. When simulating affordance options, experts were asked to create quick sketches for several functional affordances, and to select a set of options that would align to a desirable product configuration. The functional affordances with highest scores on the FTI matrix were provided together with thirty open cells dedicated for sketches (see Appendix II). For both verification and repeatability purposes, the time allowed for each exercise was carefully tracked and used to transition between each step. The total time (30 minutes) of this exercise was kept minimal to simulate the time constraints of the professional world.

The results show that on average experts responded to 79 percent of the functional affordances prompted and filled out 52.5 percent of open cells (repeats were not included in this computation). These numbers demonstrate the limited quantity of form possibilities assigned to each affordance. Although experts were instructed to use affordances to stimulate new ideas, they did not separate form from affordances. Experts were certain about how to respond to numerous users' tasks that were derived from an associated affordance. Hence, affordance implementation answers open-ended questions regarding different users' tasks. For example, the functional affordance attach-ability stimulated the creation of different shapes and form attributes that allow holding the mobile phone in a variety of new ways. Of all the different functional affordances used as a stimulus, "hold-ability" stimulated the most variety of ideas while "select-ability" was often bypassed because experts could not interpret it as a function that also depends on the digital screen of cellular phones.

In addition to documenting the quantity and variety of affordance options elaborated by experts, the study also investigated expert responses to product attributes by prompting the question: "How does this solution option fit with the overall product architecture?" Responses to this question together with most novel affordance options, demonstrated the originality of ideas generated. Table 5 illustrates novel approaches (see sketches, leftmost column) and a list of affordance options stimulated by each functional affordance.

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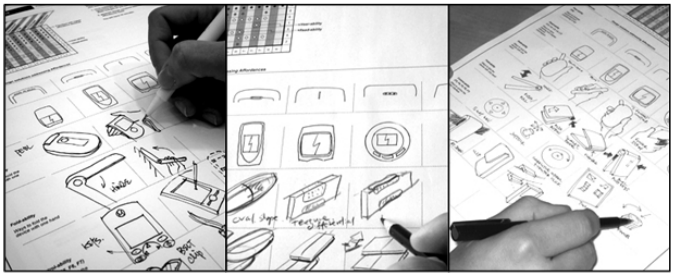
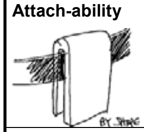
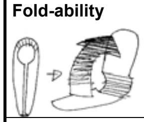
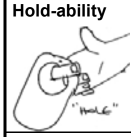
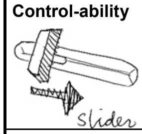
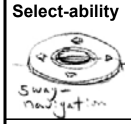
Table 5. Results of investigation II – Affordance options.



Affordances	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
Attach-ability 	1. Arm band 2. Belt 3. Collar 4. Ring 5. Pin	6. Perforation 7. Belt casing 8. Velcro	9. U-shape 10. Clip 11. Button attachment	12. Belt clip 13. Small bag 14. Lanyard	15. Lanyard 16. Strap 17. Keychain 18. Hook
Fold-ability 	1. Fold open 2. Slide vertically	3. Hinge 4. Slider 5. Rotator 6. Folding surface	7. Hinge 8. Push button 9. Wallet shape 10. Flexible hinge 11. Dual keys	12. Hinge	13. Ball hinge 14. Bending surface 15. Flexible joint 16. Rotation axis 17. Swing joint
Hold-ability 	1. Square shape 2. Oval shape 3. Texture 4. Rubberized handles 5. Chamfers on edges	6. Side grips 7. Differentiated casings 8. Indentations	9. Pen shape 10. Finger contour 11. Finger strap 12. Hole	13. Round edges 14. Pouch shape	15. Smooth edges 16. Hand indications
Control-ability 	---x---	1. Slider 2. Push-slider 3. Joystick	4. 5-way navigation 5. Joystick 6. Capacitive wheel 7. Touch screen 8. Knob	9. Control keys 10. Stylus pen 11. Screen orientation	12. Keyboard 13. Multi-tap
Charge-ability 	1. Dock station 2. USB adapter	3. Dock station 4. Induction	---x---	5. Lateral plug 6. Dock station 7. Collapsible charging prongs	8. Dock station
Select-ability 	1. 5 way navigation 2. Joystick 3. Wheel 4. Touch sensor	---x---	---x---	5. Navigation key	6. Touch pad 7. Arrows
% total cells	**60%**	**50%**	**56.6%**	**43%**	**53.3%**
Comments	Which affordance options are the best solutions?	Missing guidelines for Color, Material, and Finishing options	Form guidelines that fits with user segment, cost issues	Best option will depend on the project objectives	Need semantics of form

5. CONCLUSIONS AND FUTURE WORK

Affordance thinking provides additional understanding of relationships that may take place between technical functions and tasks that users perform. The use of the affordance concept in engineering design is a new way of studying user-device interaction and generating design solutions. In this paper, the authors review a step-by-step user-centric method for incorporating the affordance concept in product architecture design. The Function-Task-Interaction method consists of four phases: 1) User & Product Study, 2) Affordance Investigation, 3) Interaction Exploration, and 4) Simulation and Evaluation. The method considers how users' tasks relate to product functions and the design implications associated with that analysis. Affordances are inferred from user and product study.

In regards to the mobile phone case study, the two investigations highlight the importance of implementing a structured approach to the process of understanding and managing affordances. The study illustrates the challenges of detecting and describing technical functions and how choices for usability, such as the size of controls or configuration of the device, need focused attention of developers. It addressed several limitations of previous research [1] by splitting the analysis between users' and design experts responses. While users' responses helped define task analysis models, experts' exercises confirmed the accuracy of those models and provided a credible source for creativity in conceptual design.

The second investigation confirmed design experts don't need training to use the Function-Task-Interaction matrix, but reasoning to identify interactions between functions and tasks. The investigation also showed experts interpreted the matrix differently and generated alternative interactions as it provides a gradual transition from functional modeling to form implementation. The matrix, however, can be calibrated by presenting it to an interdisciplinary development team, with background in human factors, engineering, cognitive science, and interaction design. Experts can review the interactions and decide on the correctness of each interaction and related affordances. These interactions usually remain stable over time for a particular user task, but may change when different functions come into effect. In addition, an extension of the case study can suggest future product architecture configurations, especially for products that are merging functionality of other products (e.g., mobile phones and digital cameras). This is because the method can provide understanding about users and how their requirements should be balanced when merging products with distinct functions.

Finally, this study has provided insights into the role of affordances in the design process; but it has raised many questions as well. For example, how to facilitate the affordance selection process in reference to an existing product portfolio, how to expand the user-centric vocabulary for all human senses, and how to integrate users' responses regarding digital functionalities. Further research work will focus on integrating these aspects of the product architecture process. The authors also intend to further develop a computerized design repository tool that will support the methodology proposed. The system may support the creation and maintenance of a data base of examples of past affordance options, which could store not only the solution, but also the process that led to the solution.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] Galvao, A. and Sato, K., 2005, "Affordances in Product Architecture: Linking Technical Functions and Users' Tasks", Proceedings of DETC05-84525, Long Beach, California.

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[2] Kirwan, B. and Ainsworth, L.K., 1992, *A Guide to Task Analysis*, Taylor and Francis, London.

[3] Diaper, D., 1989, *Task Analysis for human computer interaction*, Ellis Horwood, Chichester, England.

[4] Shepherd, A., 1989, in Diaper (Ed.), *Task Analysis for human computer interaction,* pp.210-237, Ellis Horwood, Chichester, England.

[5] Lee, Y., 2004, "Software review: Review of the Tools for the Cognitive Task Analysis," Educational Technology & Society, 7(1):130-139.

[6] Mori, G., Paterno, F. and Santoro, C., 2002, "CTTE: Support for Developing and Analyzing Task Models for Interactive System Design," IEEE Transactions on Software Engineering, 28(9).

[7] Stuart, J. and Penn, R., 2004, "TaskArchitect: taking the work out of task analysis," Proceedings of TAMODIA'2004 Conference, pp.145-154, Prague, Czech Republic.

[8] Pahl, G. and Beitz, W., 1988, *Engineering Design: A Systematic Approach*, Springer-Verlag, London

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

[10] Hundal, M., 1990, "A Systematic Method for Developing Function Structures, Solutions and Concept Variants," Mechanism and Machine Theory, 25(3):243-256.

[11] Hubka, V., 1984, *Principles of Engineering Design*, W. E. Eder. Butterworths Publishers, London.

[12] Otto, K. and Wood, K., 2001, *Product Design – Techniques in Reverse Engineering and New Product Development*, Prentice Hall, New Jersey.

[13] Kirschman, C.F., Fadel, G.M., 1998, "Classifying Functions for Mechanical Design," Journal of Mechanical Design, Transactions of the ASME, 120(3):475-482.

[14] Ulrich, K., and Eppinger, S.D., 1995, *Product Design and Development*, McGraw-Hill Inc., New York, NY.

[15] Stone, R. and Wood, K., 2000, "Development of a Functional Basis for Design, Journal of Mechanical Design," 122(4):359-370.

[16] Hirtz, J., Stone, R., McAdams, D., Szykman, S. and Wood, K., 2001, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," Research in Engineering Design, 13(2):65-82.

[17] McAdams, D., Stone, R., and Wood, K., 1999[a], "Functional Interdependence and Product Similarity Based on Customer Needs," The Journal of Research in Engineering Design, 11(1):1-19.

[18] Bohm, M.R., Vucovich, J.P., and Stone, R.B., 2005, "Capturing Creativity: Using a Design Repository to Drive Concept Innovation," Proceedings of DETC05/CIE-85105, Long Beach, California.

[19] Stone, R., Wood, K., and Crawford, R., 1998, "A Heuristic Method to Identify Modules from a Functional Description of a Product," Proceedings of DETC98/DTM-5642, Atlanta, GA.

[20] Maier, J.R.A., and Fadel, G.M., 2003, "Affordance-based Methods for Design," Proceedings of DETC03/DTM-48673, 3:785-794, Chicago, IL.

[21] Gibson, J., 1979, The Ecological approach to Visual Perception, Houghton Mifflin Company, Boston.

[22] Norman, D.A., 1988, *The Psychology of Everyday Things*, Basic Books, New York, NY.

[23] Stone, R.B., Wood, K. L., and Crawford, R. H., 2000, "A Heuristic Method for Identifying Modules for Product Architectures," Design Studies, 21(1):5-31.

[24] Steward D.V., 1981, "The design Structure System: A Method for Managing the Design of Complex Systems," IEEE Transaction on Eng. Management, 28(3):71-74.

[25] Computer Industry Almanac, 2005, "China Tops Cellular Subscriber Top 15 Ranking". Retrieved May 18, 2006, from http://www.c-i-a.com/pr0905.htm.

[26] Shah, J. J., Santosh, V. K., and Hernandez, N., 2000, "Guidelines for experimental evaluation of idea generation methods," Proceedings of DETC2000/DTM, Baltimore MD.

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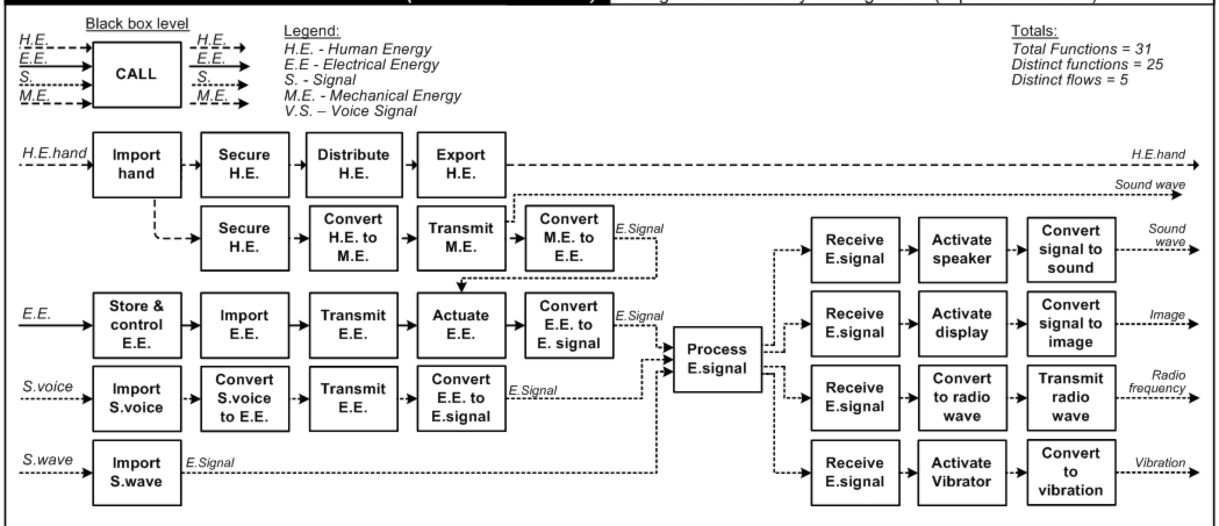
APPENDIX I – Results from investigations I and II

A - Functional Model of a Mobile Phone (Clam Architecture)

Diagram calibrated by investigation II (expert assessment)



B - Functional-Task-Interaction matrix

FTI matrix for operating a mobile phone

Interaction types
- ◆ Physical interaction = 1
- ◇ Cognitive interaction = 1
- ◈ Physical and Cognitive interactions = 2

Only functions that interact with users were listed

Technical functions / User Tasks	1. Check Cell Phone	2. Reach Cell Phone	3. Activate Cell Phone	4. Find phone #	5. Lookup phonebook	6. Select phone #	7. Place CALL	8. Talk	9. Hear	10. Find signal	11. Terminate CALL	12. Store Cell Phone	
A. Import S.voice								◇					1
B. Import hand	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	12
C. Export H.E.	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	◆	12
D. Transmit M.E.			◈	◈	◈	◈	◈			◈			6
E. Store & Control E.E.			◇	◇	◇	◇	◇	◇	◇	◇			8
F. Convert signal to sound									◇				1
G. Convert signal to image			◇	◇	◇	◇	◇						5
H. Transmit radio wave			◇				◇	◇	◇	◇			5
I. Convert to vibration			◈				◈						2
Affordance Index (∑)	2	2	9	6	6	6	9	5	5	6	2	2	52 / 60

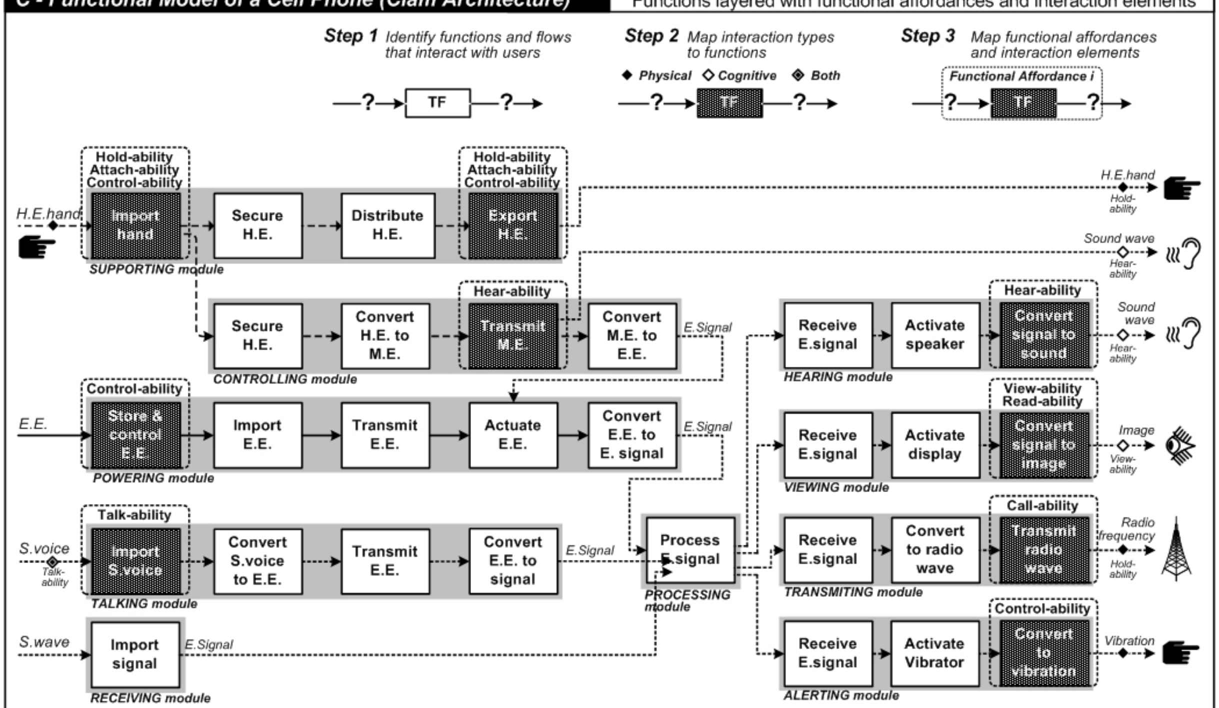
Converse-ability
Hold-/ Attach-/ Control-/ Fold-/ Select-/
Control-/ Fold-/ Select-/ Hear-ability
Control-ability
Sound-/ Hear-ability
View-ability / Read-ability
Call-ability
Control-ability

Functions with higher affordance demands

Tasks with higher affordance dependance

C - Functional Model of a Cell Phone (Clam Architecture)

Functions layered with functional affordances and interaction elements



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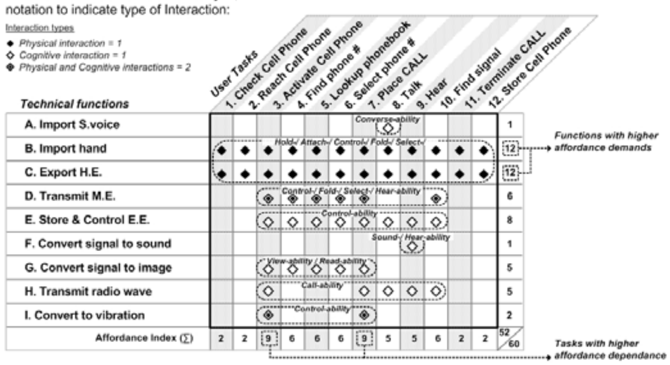
APPENDIX II – Instructions provided to experts

Function-Task-Interaction matrix and affordance exercise

Product: Cellular phone

Finding interaction points
Is the interaction human related? If yes, add notation to indicate type of Interaction:



This matrix relates technical functions and users' tasks for placing a call with a cellular phone. Examine this diagram and use it as a reference in the following exercises.

Exercise 1.
Confirm interaction points in the FTI matrix that represent the affordances listed below. Make changes as you see fit.

Exercise 2.
Generate affordance options addressing each functional affordance

Exercise 3.
Rank affordance options

You will have 30 minutes to complete all three exercises

Functional Affordances	*Affordance options*
Hear-ability *Ways to indicate sound exit and positioning of ear*	
Read-ability *Ways to allow reading and display relevant information*	
Hold-ability *Ways to hold the device with one hand*	
Fold-ability *Ways to fold the device with one hand*	
Control-ability *Ways to control the User Interface*	
Attach-ability *Ways to attach the device to belt*	
Select-ability *Ways to select with one hand*	
Charge-ability *Ways to charge the device*	

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