EXPERIMENTS COMPARING FUNCTION STRUCTURES TO AFFORDANCE STRUCTURES

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ABSTRACT

The objective of the reported experiments is to quantify the differences between two different representations of a product: function structures commonly used in systematic engineering design, and affordance structures as developed by the authors in previous work. Four consumer products are analyzed using a product tear-down strategy, and function structures from the literature are utilized where available. System level, sub-system level, and component level function structures are studied for each product. Affordance structures and Affordance-Structure Matrices (ASMs) are also generated for each product. Comparisons are made between function structures and affordance structures at each level of abstraction based on the number and types of entities and number and types of flows in each representation. During the course of the experiments, additional metrics were added to the ASM including total helpful relationships, total harmful relationships, and the percent difference between helpful and harmful relationships. Function structures were also formatted to show force flows as distinct from energy flows to reduce ambiguity. The data from the sub-system and component level function structures show that they are consistently dominated by energy and material flows (50% and 48% respectively), while information flows account for only 2% of the flows captured. The data from the affordance structures show that more helpful than harmful relationships tend to be captured (between 60% and 80%). Quantitatively, the component level function structures captured on average 24 functions and 44 flows, while comparable ASMs captured on average 20 components, 14 affordances, and 36 intra-domain relationships. Qualitatively, the principal advantage of the function based representations is the ability to capture different kinds of flows between functions. The principal advantage of the affordance based representations is the ability to distinguish between helpful and harmful relationships and specific user groups.

Keywords: affordance, function, representation

1   INTRODUCTION

One of the first steps in popular function based systematic design methods and their derivatives is the creation of some type of function structure, a graphical representation of required functions and some relationships between them [1-2]. The purpose of a function structure is to organize the functions of an artifact in a coherent manner. One type of function structure called a function tree organizes functions hierarchically, from a top-level general description of the product function down to low level "atomic" functions that can be decomposed no further.

Another type of function structure organizes functions in terms of flows—specifically flows of energy, material, and information through and between product functions [1]. This type of function structure can, but often does not, capture the hierarchy that a function tree captures. More often, separate function flow based structures are created to show different levels of hierarchy [2]. For example, a "black box" function structure shows the inputs and outputs to the system at the system level, but does not show sub-systems or individual components.

The purpose of an affordance structure is similar to that of a function structure in that, whereas a function structure organizes functions, an affordance structure organizes affordances. However, because of the different properties of functions and affordances, affordance structures cannot be organized in the same ways as function structures. Of particular interest in an affordance structure is which affordances are positive and which are negative, and which pertain to users (Artifact-User Affordances – AUA), and which pertain to other artifacts (Artifact-Artifact Affordances – AAA). A more detailed type of affordance structure, the Affordance Structure Matrix (ASM) maps affordances

to individual components. The creation of various types of affordance structures has been discussed by the authors in previous work [3-5].

The objective of the research reported in this paper is to quantify the differences between function structures and affordance structures and to explore the advantages of added information in either structure.

2   EXPERIMENTAL PROCEDURE

In the experiments we disassembled a Eureka bagless upright vacuum, a Presto hot air popcorn popper, a fruit/vegetable peeler, and an electric pencil sharpener (see Figure 1). These four items were chosen because they already had function structures available in the literature [2] for them and were easy and relatively inexpensive to obtain. The four products are also at a manageable level of complexity, yet exhibit a variety of internal mechanisms and user interface issues. System level (black box) function structures as well as sub-system level and component level function structures were created for each product based on the teardown analysis of each product following the methods in [2]. Affordance structures for all four of these products were generated using the procedure from [5], as well as Affordance-Structure Matrices using the procedure from [3-5].

| a. Eureka bagless upright | b. Presto hot air popcorn popper | c. Fruit / vegetable peeler | d. Electric pencil sharpener |

Figure 1: Products for Comparison

Once the affordance structures were created, they were compared with the function structures. The amount of information was quantified in each, according to the metrics shown in Table 1 below.

Table 1: Metrics to Quantify

Function Structures	Affordance Structures
Number of Functions	Number of Affordances
Number of Flows (energy, material and information)	Number of User Groups
Number of Levels of Abstraction	Number of Levels of Abstraction
	Number of Priority Levels

Observations were made following the generation of each representation and on the trends in the numerical data, as discussed in the next section. In particular we were interested in the respective advantages of the function based representations versus the affordance based representations and vice versa.

3   RESULTS

The individual function structures, affordance structures, and Affordance-Structure Matrices for the popcorn popper are shown in the appendices. The function structures, affordance structures, and Affordance-Structure Matrices for the other products are not included in this paper due to space limitations. The information contained in the functional representations for all of the products is summarized in Tables 2-4.

*Table 2: Information contained in the **system** level function structures for each product*

	Vacuum Cleaner	Popcorn Popper	Fruit / Vegetable Peeler	Pencil Sharpener
Number of functions	1	1	1	1
Number of Energy Flows	3	3	2	3
Number of Material Flows	6	6	5	5
Number of Information Flows	0	0	0	0
Number of Applied Force Flows	0	0	0	0
Number of Generated Force Flows	0	0	0	0
Number of Internal Force Flows	0	0	0	0
Total Flows	9	9	7	8

*Table 3: Information contained in the **subsystem** / Otto and Wood function structures for each product*

	Vacuum Cleaner	Popcorn Popper	Fruit / Vegetable Peeler	Pencil Sharpener	Mean	Mean Percent
Number of functions	15	20	21	16	18	
Number of Energy Flows	11=46%	14=39%	24=63%	16=53%	16	50%
Number of Material Flows	13=54%	22=61%	12=32%	13=43%	15	48%
Number of Information Flows	0=0%	0=0%	2=5%	1=3%	1	2%
Number of Applied Force Flows	0=0%	0=0%	0=0%	0=0%	0	0%
Number of Generated Force Flows	0=0%	0=0%	0=0%	0=0%	0	0%
Number of Internal Force Flows	0=0%	0=0%	0=0%	0=0%	0	0%
Total Flows	24	36	38	30	32	

*Table 4: Information contained in the **component** level function structures for each product*

	Vacuum Cleaner	Popcorn Popper	Fruit / Vegetable Peeler	Pencil Sharpener	Mean	Mean Percent
Number of functions	36	22	20	17	24	
Number of Energy Flows	7=13%	14=25%	5=13%	6=21%	8	18%
Number of Material Flows	14=26%	18=33%	6=16%	9=32%	12	27%
Number of Information Flows	0=0%	0=0%	1=3%	1=4%	1	2%
Number of Applied Force Flows	11=20%	1=2%	3=8%	1=4%	4	8%
Number of Generated Force Flows	1=2%	5=9%	4=11%	2=7%	3	7%
Number of Internal Force Flows	21=39%	17=31%	19=50%	9=32%	17	38%
Total Flows	54	55	38	28	44	

The information in the affordance structures is shown in Tables 5-9.

*Table 5: Information contained in the **affordance list** for each product*

	Vacuum Cleaner	Popcorn Popper	Fruit / Vegetable Peeler	Pencil Sharpener	Mean	Mean Percent
Number of Positive Affordances	9=56%	8=44%	7=58%	6=67%	8	56%
Number of Negative Affordances	7=44%	10=56%	5=42%	3=33%	6	44%
Total Number of Affordances	16	18	12	9	14	

*Table 6: Information contained in the **prioritized affordance list** for each product*

	Vacuum Cleaner	Popcorn Popper	Fruit / Vegetable Peeler	Pencil Sharpener	Mean	Mean Percent
Number of Positive Affordances	15=63%	13=52%	12=63%	11=69%	13	62%
Number of Negative Affordances	9=38%	12=48%	7=37%	5=31%	8	38%
Total Number of Affordances	24	25	19	16	21	
Number of Priority Levels	5	5	4	4	5	

Table 7: Information contained in the **affordance list organized by user group** for each product

	Vacuum Cleaner	Popcorn Popper	Fruit / Vegetable Peeler	Pencil Sharpener	Mean	Mean Percent
Number of Positive Affordances	23=56%	19=51%	18=56%	17=63%	19	57%
Number of Negative Affordances	18=44%	18=49%	14=44%	10=37%	15	43%
Total Number of Affordances	41	37	32	27	34	
Number of User Groups	4	4	4	4	4	

Table 8: Information contained in the **topical affordance structure** for each product

	Vacuum Cleaner	Popcorn Popper	Fruit / Vegetable Peeler	Pencil Sharpener	Mean
Total Number of Affordances	24	27	21	18	23
Number of Links	24	27	21	18	23

Note that the total number of affordances is always equal to the number of links. This is guaranteed by the way the affordance structure is organized.

Table 9: Information contained in the **Affordance Structure Matrix** for each product

	Vacuum Cleaner	Popcorn Popper	Fruit / Vegetable Peeler	Pencil Sharpener	Mean
Number of Parts	24	17	23	15	20
Number of Affordances	16	18	12	9	14
Number of Helpful Relationships	71	55	37	22	46
Number of Harmful Relationships	31	37	10	6	21
Helpful to Harmful Ratio	2.3:1	1.5:1	3.7:1	3.7:1	2.8:1
Total Relationships between Parts and Affordances	102	92	47	28	67
Number of Relationships between Parts	32	31	26	21	28
Number of Relationships between Affordances	9	11	7	8	9

4   OBSERVATIONS ON THE DATA

4.1 Observations on the Functional Representations

The function structures in Otto and Wood do not distinguish force flows from other types of flows, which leads to confusion in the diagrams because force is represented through different types of flows, though most often it is labeled as energy. We noted that force is not a typical flow, in that it acts on both the part receiving the force and the part that initiates the force. We also thought that it was not appropriate to consider force an energy flow since force and energy are distinct physical concepts with different units. In the literature on the functional basis vocabulary [6], force is included as a "bond graph based complement" of energy following the approach of Karnop et al. [7] in their text on system dynamics. However, Karnop and coauthors simply state the physical equations that "power can be expressed as the product of a force and a velocity for a multiport [a physical system with one or more

ports] in which mechanical translation is involved, as the product of voltage and current for an electrical port, and as the product of pressure and volume flow rate for a port at which hydraulic power is interchanged" [7]. Thus in their bond graphs, when forces enter the port of a mechanical system, velocity leaves another port. However in bond graphs, every bond is drawn with the same style line; i.e., there is no distinction as in function diagrams between energy, material, and information flows. This difference is important in function structures, and drawing both energy flows and forces with the same style arrow, while appropriate in a bond graph, results in a loss of information in function structures.

To show function flows as distinct from energy flows, in our function structures, force flows are shown with colored lines. After introducing this change, we noticed that we would be able to further clarify the diagram by differentiating between three types of force flow: applied force, generated force and internal force. These force flows all have double headed arrows to represent that the force is acting on both parts (i.e., Newton's third law).

Examining the data in Tables 3 and 4, it is evident that the flows in the sub-system and component level function structures are nearly equally dominated by energy and material flows (50% and 48% of the flows at the subsystem level respectively), while information flows account for only 2% of the flows captured in the subsystem level function structures. With the introduction of force flows at the component level, force flows dominate every other type of flow in the diagram.

One ambiguity in some function structures is that 'hand' is shown going into the system, even though the hand does not actually enter the system. In these cases, usually the hand is providing something, such as pressure, necessary for the operation of the system, but the hand itself remains outside the system. In our function structures we added an explicit boundary around the system showing which flows enter and exit the system. Thereby we are able to show that a human hand does not itself enter the system, but the force the hand exerts on the artifact does. Drawing an explicit system boundary is consistent with procedure for formulating function in Pahl and Beitz [1], e.g., as shown in their "function structure for the packing of carpet squares".

Also, in the function structures from Otto and Wood [2], vibrations are consistently shown as exiting the system. We think it is worth noting that vibrational energy can only exit the system in the form of noise or mechanically shaking another system.

We also noted that function structures can only be created for a specific functionality of the product. Functions that do not have flows coming out of them represent parts that are not used in the selected functionality of the device. For example, the function 'store power cord' which is embodied by the power cord holder is not used during the functionality of a vacuum cleaner cleaning a carpet since in that functionality the power cord is not stored. A separate function structure must be created for each functionality (e.g., cleaning a floor with a vacuum cleaner versus cleaning drapes using various attachments). In contrast, an Affordance-Structure Matrix can represent multiple uses of the product in the same matrix.

4.2 Observations on the Affordance-Based Representations

Examining the data in Tables 5-8, more positive affordances than negative affordances are captured for three out of four products studied. The most information is contained in the affordance structure organized by user group than in any of the other representations except for the Affordance-Structure Matrix.

Examining the data in Table 9 for the affordance structure matrices, all four products had between 60 and 80 percent of the total relationships between parts and affordances to be helpful. There are always more relationships between parts than between affordances. The number of relationships does not seem to be dictated by the number of parts or affordances.

In the Affordance-Structure Matrix, a distinction was made between a part that causes a negative affordance and a part that protects the user from a negative affordance. A distinction was also made between a part that helps cause a positive affordance and a part that makes the positive affordance more difficult. Helpful relationships are marked with '+' and harmful relationships are marked with '-'. This is an extension [cf., 4] of the original affordance structure matrix [3] which did not make a distinction between types of relationships, marking all relationships with 'x'. Relationships between parts or between affordances are still marked with 'x'.

The percentage of helpful and harmful relationships was computed and then used to calculate a percent difference. Large positive percent differences are representative of an affordance that has

many more helpful parts than harmful or a part that has many more helpful affordances than harmful. A zero percent difference represents an equal number of helpful and harmful parts or affordances. A large negative difference represents a larger number of harmful parts or affordances than helpful parts or affordances.

One issue we realized with looking at objects from a reverse engineering perspective is that there is no way to capture a negative affordance that was completely eliminated in the design phase. From the design perspective, the undesired operation could be classified as a negative affordance and designed against, but once it has been completely eliminated it can no longer be captured. Hence the negative affordances shown in an Affordance-Structure Matrix represent opportunities for future improvement.

4.3 Comparison of the Data Captured in Function and Affordance Structures

The results have shown first that function structures and affordance structures capture qualitatively different kinds of information. Thus, a raw comparison of the number of flows in a function structure and the number of affordances captured in an affordance structure is not a very meaningful comparison.

As expected, the more detailed the representation, the more information is captured. Thus, for example, a component level function structure always contained more information than a sub-system level or system level function structure.

Function structures and affordance structures are on somewhat parallel levels of abstraction, as they both describe the products without reference to the product's physical embodiment. The Affordance-Structure Matrix, in contrast, allows for mapping to product structure, and there is no analogous function structure studied in this research. However, function to component mappings in matrix form have been studied by the authors in other work [8-9].

The principal advantage of the function based representations is the ability to capture different kinds of flows between functions. The principal advantage of the affordance based representations is the ability to distinguish between helpful and harmful relationships and specific user groups. The ability to capture flows is intrinsic to the nature of functions as representing transformative processes, whereas the ability to capture helpful and harmful relationships and user groups is intrinsic to the nature of affordances which are defined as being either positive or negative and specific to individual users.

For these reasons, functional representations and affordance representations are qualitatively different and irreconcilable. Therefore there is separate and unique value in both function based and affordance based representations. Both representations provide separate and valuable analysis perspectives to support engineering design.

5. CONCLUSIONS AND FUTURE WORK

The differences between function structures and affordance structures have been quantified and qualitative comparisons made for four different consumer products. The separate analysis perspectives offered by both function structures and affordance structures suggest that the different structures cannot be used as substitutes for one another; rather their independent data should be collected and used to support analysis both from functional and affordance-based perspectives. Suggested directions of future work therefore include methodological support for the combined use of functional and affordance-based data, and applying function based and affordance based methods to the design of new products, not just in reverse engineering of existing products.

REFERENCES

[1] Pahl G. and Beitz, W. *Engineering Design: A Systematic Approach* (2nd ed) (Springer-Verlag, New York) 1996.

[2] Otto K., and Wood K. *Product Design: Techniques in Reverse Engineering and New Product Development*. (Englewood Cliffs, NJ: Prentice-Hall) 2001.

[3] Maier J. R. A., Ezhilan T., and Fadel G. M. The Affordance Structure Matrix - A Concept Exploration and Attention Directing Tool for Affordance Based Design, *Proceedings of ASME Design Theory and Methodology Conference*, Las Vegas, NV. Paper no. DETC2007-34526.

[4] Maier J. R. A., Sandel J. and Fadel G. M.. Extending the Affordance Structure Matrix - Mapping Design Structure and Requirements to Behavior, *Proceedings of DSM'08*, Stockholm, Sweden. 11-12 November, 2008.

[5] Maier J. R. A. and Fadel G. M. Affordance Based Methods for Innovative Design, Redesign, and Reverse Engineering. *Research in Engineering Design* (in press).

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

[7] Karnop D. C., Margolis D. L., and Rosenberg R. C. *Systems Dynamics: A Unified Approach* (2nd ed) (John Wiley & Sons, New York) 1990.

[8] Mocko, G. M., G. M. Fadel, J. D. Summers, J. R. A. Maier, and T. Ezhilan. A Systematic Method for Modelling and Analysing Conceptual Design Information. *Proceedings of 9th International Design Structure Matrix Conference, DSM'07*, 16-18 October, 2007, Munich, Germany. Paper no. DSM'07/13.

[9] Mocko, G., Maier, J. R. A., Ezhilan, T., Fadel, G. M., Summers, J. D., Teegavarapu, S. A Modeling Scheme for Capturing and Analyzing Conceptual Design Information: An Application to the Hair Dryer Example and Comparison to Existing Literature. *Proceedings of the 16th International Conference on Engineering Design (ICED-07)*, August 28-31, 2007, Paris, France.

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APPENDIX A: FUNCTIONAL REPRESENTATIONS FOR THE PRESTO POPCORN POPPER
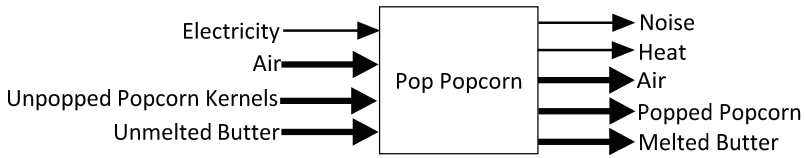
Figure A1: System Level Function Structure for the Presto Popcorn Popper
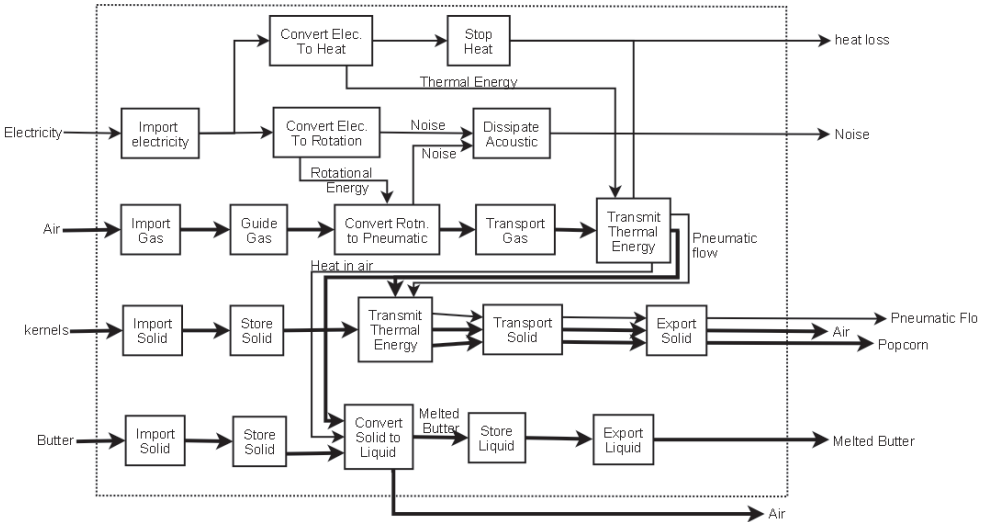
Figure A2: Otto and Wood [2] Function Structure for the Presto Popcorn Popper
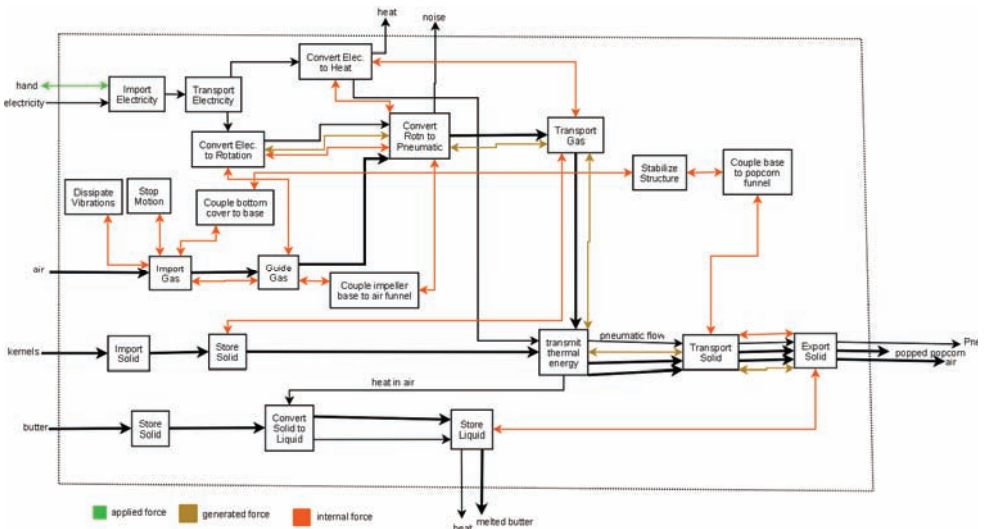
Figure A3: Component Level Function Structure for the Presto Popcorn Popper

APPENDIX B: AFFORDANCE-BASED REPRESENTATIONS

Table B1: Affordance List, not including annotations for the Presto Popcorn Popper

Positive Affordances:	Negative Affordances:
Popcorn Popability	Acoustic Annoyability
Storability	User Burnability
Stability	Deformability
Kernel Containability	Air Flow Path Blockability
Butter Meltability	Kernel Retainability
Popcorn Measureability	Kernel Expellability
Popcorn Expellability	Electric Shockability
Cleanability	Kernel Burnability
	Bowl Meltability / Burnability
	Popcorn Scatterability

Table B2: Prioritized Affordances, not including annotations for the Presto Popcorn Popper

Priority	Positive Affordances:	Negative Affordances:
1	Popcorn Popability Kernel Containability Popcorn Expellability Butter Meltability	Air Flow Path Blockability Kernel Retainability Kernel Expellability
2	Popcorn Measureability Cleanability	User Burnability Electric Shockability Popcorn Scatterability
3	Storability Stability	Acoustic Annoyability Kernel Burnability Bowl Meltability/Burnability
4	Aesthetics	Deformability
5	Manufacture Maintenance Sustainability Retirement	Frustration Degradation

Table B3: Affordance Structure organized by user group, not including annotations for the Presto Popcorn Popper

User Group	Positive Affordances:	Negative Affordances:
Manufacturing Workers	Manufacture Storability Stability	Deformability Frustration Electric Shockability
Freight Handlers	Storability Stability	Frustration
End users	Popcorn Popability Storability Stability Kernel Containability Butter Meltability Popcorn Measureability Popcorn Expellability Cleanability Aesthetics Sustainability Maintenance	Acoustic Annoyability User Burnability Deformability Air Flow Path Blockability Kernel Retainability Kernel Expellability Electric Shockability Kernel Burnability Bowl Meltabilty / Burnability Popcorn Scatterability Frustration Degradation
Disposal Workers	Retirement Sustainability Storability	Frustration Electric Shockability

Figure B1: Topical Affordance Structure for the Presto Popcorn Popper

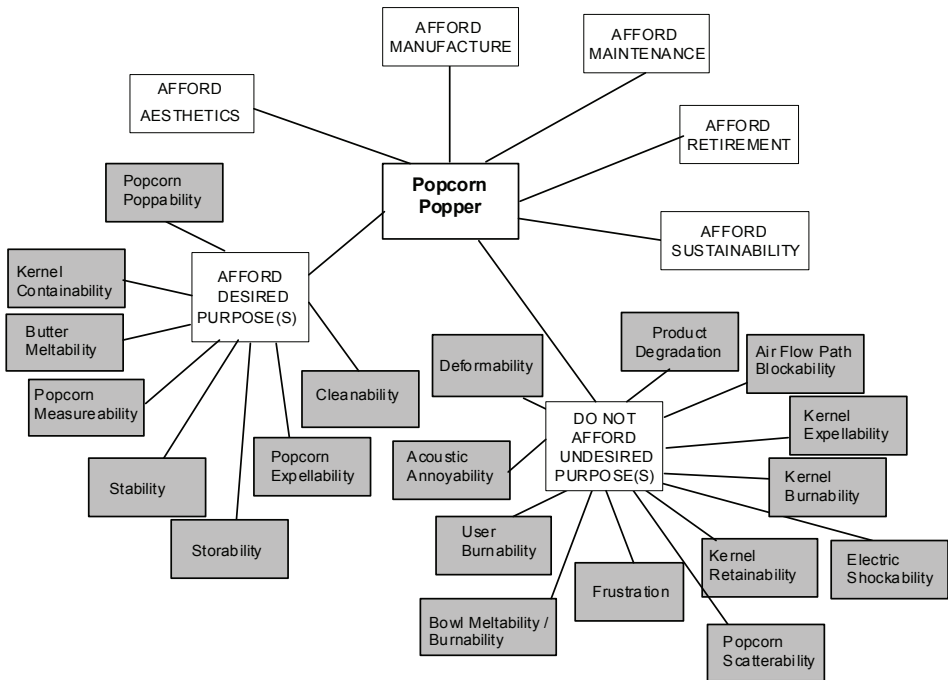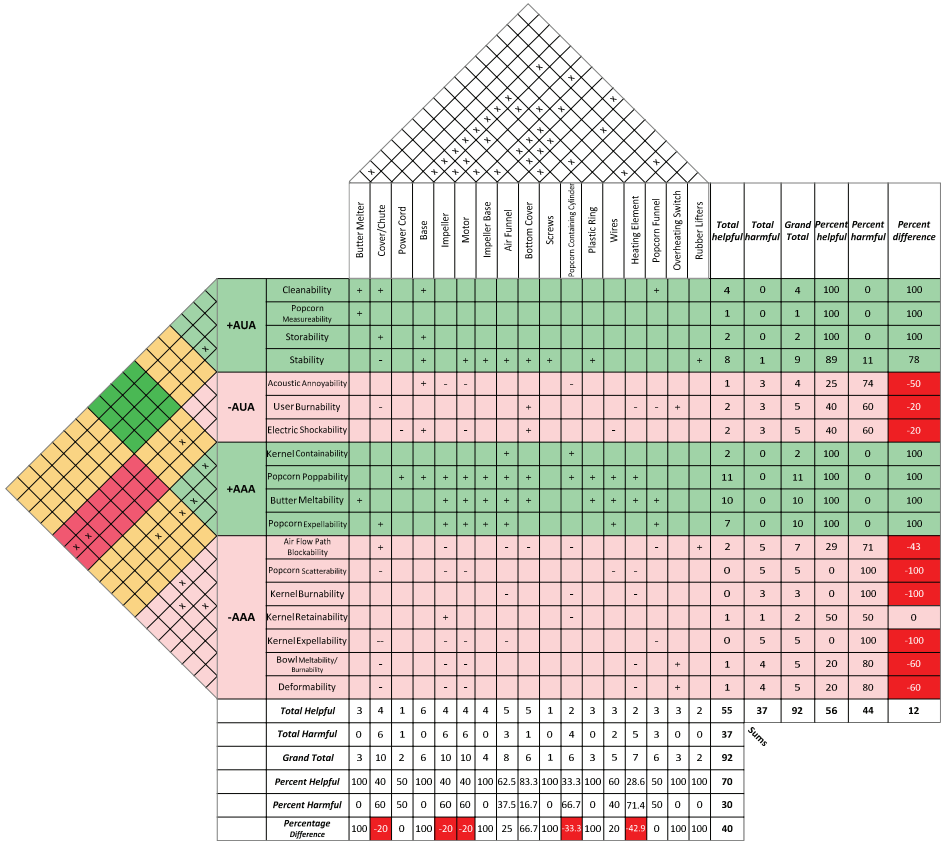Figure B2: Affordance Structure Matrix for the Presto Popcorn Popper

		Butter Melter	Cover/Chute	Power Cord	Base	Impeller	Motor	Impeller Base	Air Funnel	Bottom Cover	Screws	Popcorn Containing Cylinder	Plastic Ring	Wires	Heating Element	Popcorn Funnel	Overheating Switch	Rubber Lifters	Total helpful	Total harmful	Grand Total	Percent helpful	Percent harmful	Percent difference
+AUA	Cleanability	+	+		+												+		4	0	4	100	0	100
	Popcorn Measureability	+																	1	0	1	100	0	100
	Storability		+		+														2	0	2	100	0	100
	Stability		-		+		+	+	+	+	+		+					+	8	1	9	89	11	78
-AUA	Acoustic Annoyability		+		+	-	-					-							1	3	4	25	74	-50
	User Burnability		-							+					-	-	+		2	3	5	40	60	-20
	Electric Shockability			-	+		-			+				-					2	3	5	40	60	-20
+AAA	Kernel Containability								+			+							2	0	2	100	0	100
	Popcorn Poppability		+		+	+	+	+	+	+			+	+	+	+			11	0	11	100	0	100
	Butter Meltability	+				+	+	+	+	+				+	+	+	+		10	0	10	100	0	100
	Popcorn Expellability		+			+	+	+	+						+		+		7	0	10	100	0	100
-AAA	Air Flow Path Blockability		+			-			-	-			-			-		+	2	5	7	29	71	-43
	Popcorn Scatterability		-			-	-								-	-			0	5	5	0	100	-100
	Kernel Burnability								-				-		-				0	3	3	0	100	-100
	Kernel Retainability				+								-						1	1	2	50	50	0
	Kernel Expellability		--			-	-		-							-			0	5	5	0	100	-100
	Bowl Meltability/Burnability		-			-									-		+		1	4	5	20	80	-60
	Deformability		-			-	-								-		+		1	4	5	20	80	-60
	Total Helpful	3	4	1	6	4	4	4	5	5	1	2	3	3	2	3	3	2	55	37	92	56	44	12
	Total Harmful	0	6	1	0	6	6	0	3	1	0	4	0	2	5	3	0	0	37					
	Grand Total	3	10	2	6	10	10	4	8	6	1	6	3	5	7	6	3	2	92					
	Percent Helpful	100	40	50	100	40	40	100	62.5	83.3	100	33.3	100	60	28.6	50	100	100	70					
	Percent Harmful	0	60	50	0	60	60	0	37.5	16.7	0	66.7	0	40	71.4	50	0	0	30					
	Percentage Difference	100	-20	0	100	-20	-20	100	25	66.7	100	-33.3	100	20	-42.9	0	100	100	40					