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HIERARCHICAL AFFORDANCE MODELING

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ABSTRACT
The theory of affordances has been adapted by the authors into a comprehensive high-level approach to design known as affordance based design. One of the features that distinguishes the affordance based approach from function based approaches is that affordances are *form dependent*. Designers can take advantage of this property during conceptual design by analyzing how well the form (or structure) of individual concepts satisfy the desired and undesired (positive and negative) affordances for the project. In other work, we have introduced a matrix based tool called the Affordance Structure Matrix (ASM). However, in the products we have studied to date, typically the desired and undesired affordances at the system level are mapped to individual parts at the component level. Our focus in this paper is utilizing the ASM to study how the satisfaction of affordances propagates hierarchically upward from the component level to the sub-system level, and finally system level. A hair-dryer is used as an example system to demonstrate the approach. We illustrate how component level affordances propagate upward from the component to the sub-system and system level, and how new affordances emerge at higher levels of hierearchy.

Keywords: affordance, hierarchy, modeling

1 INTRODUCTION
The theory of affordances has been adapted by the authors into a comprehensive high-level approach to design known as affordance based design [1]. One of the features that distinguishes the affordance based approach from function based approaches is that affordances are form dependent. Designers can take advantage of this property during conceptual design by analyzing how well the form (or structure) of individual concepts satisfy the desired and undesired (positive and negative) affordances for the project. In other work, we have introduced a matrix based tool called the Affordance Structure Matrix (ASM) [2-4].

The Affordance Structure Matrix is a tool to compare requirements information in terms of affordances, with physical structure, during the conceptual stage of design. Requirements are organized into four categories: positive Artifact-User Affordances (+AUA), such as reliability, negative Artifact-User Affordances (-AUA), such as burning the user, positive Artifact-Artifact Affordances (+AAA), such as conducting electricity, and negative Artifact-Artifact Affordances (-AAA), such as damage to a device by over-heating. The interior of the ASM is populated by considering whether each component of a product has a helpful (+), harmful (-) or no ( ) relationship to each affordance. Other quantitative numbering schemes have been considered by the authors in separate work [13]. For a detailed description of the ASM and instructions for populating an ASM, the reader is referred to our previous work [2-4].

An important difference between an ASM and other similar matrices such as the House of Quality and Design Structure Matrices is the ability to distinguish whether relationships are helpful or harmful (+/-), not just existence or non-existence. The identification of helpful and harmful relationships enables additional metrics. In particular, the total number of components (or sub-systems) that are helpful with respect to each affordance can be calculated, as well as the total number of components (or sub-systems) that are harmful with respect to each affordance.

Similarly, the total number of affordances with which each component (or sub-system) has a helpful relationship can be calculated. The total number of affordances with which each component (or sub-system) has a harmful relationship can also be calculated.

For each component or sub-system, comparing the relative percentage of helpful to harmful relationships gives a rough indication of whether that component is doing more harm than good. For each affordance, comparing the relative percentage of helpful to harmful relationships gives a rough indication of whether more components (or sub-systems) are helping or hurting to achieve a positive affordance or protect from a negative affordance. For the overall product, the total relative percentage of helpful to harmful relationships gives a rough indication of how much room for improvement there is; i.e., compared to an ideal situation where all components or sub-systems are helpful.

In the products we have studied to date, typically the desired and undesired affordances at the system level are mapped to individual parts at the component level. Our focus in this paper is utilizing the ASM to study how the satisfaction of affordances propagates hierarchically upward from the component level to the sub-system level, and finally system level. A hair-dryer is used as an example system to demonstrate the approach.

2 HIERARCHICAL AFFORDANCE STRUCTURE MATRICES FOR A HAIR DRYER

The design of a hair dryer is chosen because it is sufficiently complex to demonstrate the hierarchical aspect of our approach without being too complex to make the presentation unwieldy. Moreover, the design of a hair dryer is a common example in the literature demonstrating similar conceptual design tools and matrix-based modeling schemes. The hair dryer system model is developed through reverse engineering and from existing literature [5-11].

A completed hierarchical ASM for a typical hairdryer is shown in Figure 1. The left side of the ASM which maps relationships between individuals is not shown for the sake of brevity and because these relationships do not change with changes in hierarchy of the system structure. The roof of the ASM which maps relationships between individual components is likewise not shown for the sake of brevity and because studies of hierarchical relationships between components in intra-domain matrices have already been well studied in the literature [12]. Note that in all the figures a cell containing "####" indicates a division by zero error.

	Affordance - Structure Matrix	Hair Dryer	1. Fan Assembly	1.1 Switch	1.2 Fan Housing	1.3 Motor	1.4 Fan Blade	2. Heating Assembly	2.1 Heating Element	2.2 Springs	2.3 Thermocouple	2.4 Temperature Switch	3. Front Housing	3.1 Heat Shield	3.2 Front Grid	3.3 Front Case	3.4 Power Cord	3.5 Switch Actuator	4. Rear Housing	4.1 Rear Housing	4.2 Screen	4.3 Grounding Wire	*Total helpful*	*Total harmful*	*Total*	*Percentage helpful*	*Percentage harmful*	*Percentage difference*
+AUA	**Hair dryability**	**1**	**1**		1	1	1	**1**	1	1			**1**		1				**0**				6	0	6	100	0	100
	Portability	**1**	**0**					**0**					**0**						**0**				0	0	0	###	###	####
	Reliability	**0**	**-1**	-1		-1		**1**	-1		1	1	**-1**				-1	-1	**1**			1	3	5	8	38	63	-25
	Comfortability	**1**	**0**					**0**					**1**			1			**1**	1			2	0	2	100	0	100
	Provide user adjustment	**1**	**1**	1				**0**					**1**					1	**0**				2	0	2	100	0	100
-AUA	**Annoying user with noise**	**1**	**0**		1		-1	**0**					**1**			1			**1**	1			3	1	4	75	25	50
	Annoying user with difficult operation	**0**	**0**					**0**					**0**						**0**				0	0	0	###	###	####
	Costing user money to operate	**-1**	**-1**			-1		**-1**	-1				**0**						**0**				0	2	2	0	100	-100
	Electric shockability	**1**	**0**		1	-1		**0**	-1	1			**1**			1	1		**1**	1		1	6	2	8	75	25	50
	Burn user	**1**	**0**					**1**	-1	1		1	**1**	1	1	1			**1**	1			6	1	7	86	14	71
	Cut or pinch user	**1**	**0**		1		-1	**0**					**1**			1			**1**	1	1		4	1	5	80	20	60
+AAA	**Provides attachment**	**1**	**0**		1			**0**					**1**			1			**1**	1			3	0	3	100	0	100
	Conducts electricity	**1**	**1**	1		1		**1**	1	1			**1**				1	1	**1**			1	7	0	7	100	0	100
	Transmits power	**1**	**1**			1		**0**					**0**						**0**				1	0	1	100	0	100
	Transfers heat	**1**	**0**					**1**		1			**0**						**0**				1	0	1	100	0	100
	Provide temperature dependent voltage	**1**	**0**					**1**			1		**0**						**0**				1	0	1	100	0	100
-AAA	**Clogged airway**	**-1**	**-1**		-1		-1	**-1**		-1			**-1**		-1				**0**	-1	1		1	5	6	17	83	-67
	Damage by overheating	**0**	**-1**			-1		**1**	-1		1	1	**0**						**0**				2	2	4	50	50	0
	total helpful	13	4	2	5	3	1	7	2	5	3	3	9	1	2	6	2	2	8	6	2	3	**48**	**19**	**67**			
	total harmful	2	4	1	1	4	3	2	5	1	0	0	2	0	1	0	1	1	0	1	0	0	**19**	sums				
	total	15	8	3	6	7	4	9	7	6	3	3	11	1	3	6	3	3	8	7	2	3	**67**					
	percent helpful	87	50	67	83	43	25	78	29	83	100	100	82	100	67	100	67	67	100	86	100	100						
	percent harmful	13	50	33	17	57	75	22	71	17	0	0	18	0	33	0	33	33	0	14	0	0						
	percentage difference	73	0	33	67	-14	-50	56	-43	67	100	100	64	100	33	100	33	33	100	71	100	100						

Figure 1. Hierarchical ASM for a hair dryer (roof and left side not shown)

As in typically done when populating an ASM [3-4], the relationships between each affordance and each component are evaluated directly where +1 represents a helpful relationship between the component and the affordance, -1 represents a harmful relationship between the component and the affordance, and 0 (or blank) represents no significant relationship.

In Figure 1, the relationship between each subsystem and each affordance is evaluated by summing the relationships across each of the components in that subsystem and then normalizing to the +1, 0, -1 numbering scheme. Similarly, the relationship between the system itself and each affordance is evaluated by summing the relationships across each of the subsystems and again normalizing to the +1, 0, -1 numbering scheme.

To investigate the affordances of the hair dryer at higher levels of the hierarchy only, Figure 2 shows a collapsed version of the ASM from Figure 1, but displaying only the system and subsystem levels. The values for the relationships in Figure 2 (and throughout the remainder of this paper) are thus not populated directly; rather they are calculated by examining the relationships at the component level as discussed above.

	Affordance - Structure Matrix	Hair Dryer	1. Fan Assembly	2. Heating Assembly	3. Front Housing	4. Rear Housing	*Total helpful*	*Total harmful*	*Total*	*Percentage helpful*	*Percentage harmful*	*Percentage difference*
+AUA	Hair dryability	1	1	1	1	0	3	0	3	100	0	100
	Portability	0	0	0	0	0	0	0	0	###	###	###
	Reliability	0	-1	1	-1	1	2	2	4	50	50	0
	Comfortability	1	0	0	1	1	2	0	2	100	0	100
	Provide user adjustment	1	1	0	1	0	2	0	2	100	0	100
-AUA	Annoying user with noise	1	0	0	1	1	2	0	2	100	0	100
	Annoying user with difficult operation	0	0	0	0	0	0	0	0	###	###	###
	Costing user money to operate	-1	-1	-1	0	0	0	2	2	0	100	-100
	Electric shockability	1	0	0	1	1	2	0	2	100	0	100
	Burn user	1	0	1	1	1	3	0	3	100	0	100
	Cut or pinch user	1	0	0	1	1	2	0	2	100	0	100
+AAA	Provides attachment	1	0	0	1	1	2	0	2	100	0	100
	Conducts electricity	1	1	1	1	1	4	0	4	100	0	100
	Transmits power	1	1	0	0	0	1	0	1	100	0	100
	Transfers heat	1	0	1	0	0	1	0	1	100	0	100
	Provide temperature dependent voltage	1	0	1	0	0	1	0	1	100	0	100
-AAA	Clogged airway	-1	-1	-1	-1	0	0	3	3	0	100	-100
	Damage by overheating	0	-1	1	0	0	1	1	2	50	50	0
	total helpful	12	4	7	9	8	28	8	36			
	total harmful	2	4	2	2	0	8	sums				
	total	14	8	9	11	8	36					
	percent helpful	86	50	78	82	100						
	percent harmful	14	50	22	18	0						
	percentage difference	71	0	56	64	100						

Figure 2. System and sub-system level hierarchical ASM for a hair dryer (roof and left side not shown)

The relationships at the system level suggest that twelve of the eighteen listed affordances are adequately satisfied, whereas four of the eighteen affordances are balanced between subsystems that are helpful and subsystems that are harmful. Finally two out of the eighteen affordances, costing the user money and clogged airways, have only harmful subsystems associated with them. Overall, the system has an 86% helpful to 14% harmful relationships, for a 71% difference. Note that costing the user money is considered only for the cost of electricity used to operate the hair dryer, and does not capture the purchase cost of the hair dryer.

Meanwhile, the relationships at the subsystem level show that the rear housing has the largest percentage difference, at 100% showing that this subsystem has no affordances captured in the ASM that need to be improved. By comparison, the fan assembly has a 0% difference, indicating that the fan assembly has an equal number of affordances that need to be improved and number of affordances that are currently satisfied.

Alternatively, the subsystem and system level relationships can be calculated additively, rather than normalizing to the +1, 0, -1 numbering scheme used at the component level. An ASM utilizing this scheme is shown in Figure 3. In other work, the authors have conducted experiments on different quantitative numbering schemes at the component level [13].

	Affordance - Structure Matrix	Hair Dryer	1. Fan Assembly	2. Heating Assembly	3. Front Housing	4. Rear Housing	*Total helpful*	*Total harmful*	*Total*	*Percentage helpful*	*Percentage harmful*	*Percentage difference*
+AUA	Hair dryability	6	3	2	1	0	6	0	6	100	0	100
	Portability	0	0	0	0	0	0	0	0	###	###	###
	Reliability	-2	-2	1	-2	1	2	4	6	33	67	-33
	Comfortability	2	0	0	1	1	2	0	2	100	0	100
	Provide user adjustment	2	1	0	1	0	2	0	2	100	0	100
-AUA	Annoying user with noise	2	0	0	1	1	2	0	2	100	0	100
	Annoying user with difficult operation	0	0	0	0	0	0	0	0	###	###	###
	Costing user money to operate	-2	-1	-1	0	0	0	2	2	0	100	-100
	Electric shockability	4	0	0	2	2	4	0	4	100	0	100
	Burn user	5	0	1	3	1	5	0	5	100	0	100
	Cut or pinch user	3	0	0	1	2	3	0	3	100	0	100
+AAA	Provides attachment	3	1	0	1	1	3	0	3	100	0	100
	Conducts electricity	7	2	2	2	1	7	0	7	100	0	100
	Transmits power	1	1	0	0	0	1	0	1	100	0	100
	Transfers heat	1	0	1	0	0	1	0	1	100	0	100
	Provide temperature dependent voltage	1	0	1	0	0	1	0	1	100	0	100
-AAA	Clogged airway	-4	-2	-1	-1	0	0	4	4	0	100	-100
	Damage by overheating	0	-1	1	0	0	1	1	2	50	50	0
	total helpful	37	8	9	13	10	**40**	**11**	**51**			
	total harmful	8	6	2	3	0	**11**	sums				
	total	45	14	11	16	10	**51**					
	percent helpful	82	57	82	81	100						
	percent harmful	18	43	18	19	0						
	percentage difference	64	14	64	63	100						

Figure 3. Additive system and sub-system level hierarchical ASM for a hair dryer (roof and left side not shown)

Comparing the relationships shown in Figure 2 with Figure 3, the principal difference is that in Figure 3, the magnitude of relationships is shown in Figure 3 and not in Figure 2. Thus, for example, we see that at the system level, the hair dryer has the most helpful relationships for the affordance of conducting electricity (a consequence of the components that conduct electricity), followed by hair dryability, and the most harmful relationships for the affordance of clogged airways. This can be seen by examining either the values in the column for the hair dryer system, or by examining the values in each row for the total helpful and total harmful values for individual affordances. It is also evident in Figure 3 that the affordance of reliability has changed from balanced between helpful and harmful relationships to having more harmful relationships. As a consequence of the change from neutral to negative for the affordance of reliability, and the increased granularity of all the relationships because of the additive number scheme, at the system level the percentage difference has decreased from 71% in Figure 2 to 64% in Figure 3, indicating more room for improvement, and more precisely where improvement is needed.

For example, in Figure 1, the components which have problems with clogged airways are specifically indicated, and there is no differentiation between them. In Figures 3, we see that the fan assembly has twice as many components with harmful relationships with clogged airways as either the heating assembly or front housing, providing the designer with insight into where to focus the redesign of the hair dryer, and which possible design tool, maybe fluid dynamics in this case, needs to be used. This information was lost with the normalization scheme applied in Figure 2, but recovered in Figure 3.

3 ON THE HIERARCHICAL PROPAGATION OF AFFORDANCES

Finally we note that in Figures 1-3, two affordances (portability and annoying the user with difficult operation) have no relationships mapped across any of the components. In the case of the hair dryer, this is because these affordances emerge at the system level, and are not the result of any individual component. The "####", which is a "division by zero" result, in the percentage difference for these two affordances is a flag to the modeler that these affordances need to be evaluated at the system level.

These system level affordances are directly related to the shape, the size, the weight, and other system level characteristics of the product. Portability for instance may be directly related to weight, to the location of the center of gravity, to the ease of grasping the object

Thus the hair-dryer example illustrates how all component level affordances such as 'hair dryability' propagate upward from the component level all the way up to the system level, but some system level affordances such as 'portability' do not propagate downward from the system level to the component level. In other words, higher levels of the hierarchy inherit lower level affordances, but new affordances emerge at higher levels of the hierarchy that are not present at lower levels.

The affordances that emerge at higher levels are those that depend on the organization of the elements at lower levels, i.e., those that are *constitutive*. The affordances that propagate upward are essentially *summative*. For a general discussion of constitutive and summative elements in system theory, the reader is referred to [14].

4 CONCLUSIONS

In conclusion, the hierarchical ASM can be used to explore how relationships propagate upwards from the component level to understand how helpful and harmful relationships emerge at the system level. As an attention directing tool, this information can be used by designers to improve specific affordances by focusing on problematic subsystems and components.

An important realization is that some affordances can be effectively studied at the component level, but at the system level, the system is indeed more than the sum of its parts, because some affordances such as portability emerge only at the system level. The shape and mass of any individual component or sub-assembly affects portability, but only the hair dryer as a whole is portable or not.

Thus modeling a system hierarchically in an ASM provides additional insight into the system's affordances over a model formulated only at the component level. The ASM provides flexibility for various numbering schemes for examining relationships at higher levels of the hierarchy. In the case of the hair dryer shown in this paper, the added numbering scheme at the subsystem and system level provides more useful engineering information than enforcing the +1, 0, -1 numbering scheme.

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