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MODELLING DIFFERENCES IN INDIVIDUAL PERCEPTIONS OF ABSTRACTED SYSTEM MODELS

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Abstract:

Engineer's often develop abstract conceptual models of products using function based languages. The expectation is that these models, even when prepared by different engineers will be similar if not identical in form. In practice, this is not at all the case, particularly when the modelling form is highly abstracted from physical reality. This paper explores a proposed method that can identify differences in system perception amongst engineers and supports the development of metrics that enable model regions where perceptions differ to be quantified and identified. These regions are suspected to be regions where creativity and innovation may be readily applicable to the system design. The work in this paper is supported by an initial pilot study as a foundation for further work.

Keywords: *State Transition Matrices, Functional Modeling, Concept Models, Abstraction, Individual Perspective*

1. Introduction

Prior to the emergence of geometric Computer-Aided Design (CAD) systems, engineers relied on hand-sketches and drafted drawings to develop design concepts. CAD systems, built on geometric primitives (a vocabulary) combined with a geometric algebra (a grammar for developing higher-order concepts from primitive components), enabled engineers to explore early design concepts on the computer. By combining CAD systems with engineering analysis and manufacturing systems, even higher-order reasoning about the performance or manufacturing of the design could be done in early design stages. However, CAD models and all the reasoning relying on it work only if form-related information (form = geometry + material [1]) is available to model. Coupled with a well-defined vocabulary and grammar this allows "differently constructed" CAD models to be translated into different CAD packages and to be broadly understood by different engineers. There is no CAD-equivalent system that provides for modelling, reasoning, and decision support, such as that afforded by geometric CAD, to the early design stages where form is not yet known.

In this abstract phase of the design process, the designer's goal is to identify the functional underpinnings that will ultimately lead to the form of the design artefact. To support this understanding, multiple model formulations have been developed to provide a link between an abstracted system concept, and the physical reality of the design artefact. However, unlike the geometric and material models underlying CAD, the models developed for this abstract domain may often exhibit multiple "correct" models, differing in the level of abstraction and differing due to individual designer perspectives. This ability for two designers to see the same system differently greatly complicates the development of any computational support tools for these modelling languages and significantly increases the difficulty to assess the true "difference" between two valid representations. Furthermore, the identification of the model elements where model perception diverges is hypothesized to represent a potential point for creative interpretation of the design.

2. Motivation and Background

It is a well-known occurrence in design whereby different designers can produce equally valid abstract simple models of the same design [2]. These differing models are likely the result of the verdicality of perception, an underlying cognitive process related to our own experiences with illusion. If we consider a classic example of illusion as shown in Figure 1, some will see a young lady, while others see an old woman. Research suggests that how you see this image is related to the preconceptions that you have when the image is shown [3]. Similarly, for a designer, the abstraction that they construct as a model of a system may be influenced by their own preconceptions about the system and the modelling process.

Figure 1. A Young Lady – Or – An Old Woman?

While several modelling processes are commonly employed, we will primarily focus on functional modelling in this paper.

2.1. Functional Models

Function-based design is an approach to model a technical system in terms of its abstract functions without commitment to a specific form, and reasoning on the system's functionality in order to perform various design tasks. The practice is well-recognized as a means of modelling design concepts in an abstract, form-neutral manner [4, 5], studying existing designs through reverse engineering [5, 6], and exploring solution variants [4, 5, 8]. Various modelling and reasoning have been proposed to perform these tasks.

Engineered artefacts are designed to serve specific purposes, and technical functions are an abstract way of describing the device's actions intended by the designer toward serving that purpose [4, 5]. The philosophy that design is a process of deriving form from function has produced multiple design models in the 1970s through the 1990s [5], mainly in the artificial intelligence community. Design texts and research suggest that analysing and thinking about design problems and products in terms of functions helps to decompose the problem [5, 9, 10], expand the search spaces [4, 5, 8], understand the workings of devices [3], and archive existing designs for later reuse [7, 11]. To do these activities in a more reliable and controlled manner, the need to formalize the domain of functions arises, and to this end, various formalisms have been proposed, both in Artificial Intelligence (AI) research and in engineering design research.

In AI research, functions are generally viewed as the result of the interaction between various aspects of the design, such as the device's structure and behaviour, the environment, and the user's intent. For example, function has been defined as "the relation between the goal of a human user and the behaviour of a system" [12]. Representations such as Function-Behaviour-Structure (FBS) [13, 14], Function-Behaviour-State (FBSt) [9], and Structure-Behaviour-Function (SBF) [15, 16] are broadly based on this view, although each supports a different types of reasoning. Other views attempt to describe functions as the device's effect [17], or using the device's viewpoint on its actions [18]. Various formalisms, in form of representations [18, 19], languages [20], ontologies [21], and software tools [9, 22] have been proposed to support reasoning based on this general view of functions. Notable examples are the FBS Modeler [18] that supports problem decomposition based on the FBS model, the IDeAL [16] and Kritik [15] tools that support analogy-based search using the SBF model, the Causal Functional Representation Language (CFRL) [23] that describes functions as cause-and-effect, and the Schemebuilder tool [22]. A more detailed account of function-based reasoning can be found in [24-26].

In engineering design, the systems-based view of functions as the transformations of material, energy, and information flows through the system is prevalent [4, 5, 8]. A second view, the Contact-and-Channel model, describes functions as the interaction between contacting surfaces [27, 28]; however, the following discussion relies only on the transformative view. A graph-based representation, the function structure [4], is commonly used to this end. The nodes are the transformative actions and the edges are the flows of material, energy, and information subject to the transformations. Tools and methods that leverage this representation have been built to assist in conceptual design tasks such as problem exploration [29], decomposition [4, 5], solution search [8], solution synthesis [31], concept generation [32], failure modelling [33], product similarity analysis [34], modelling signal flows [35, 36], and for reverse engineering tasks such as design understanding and archiving [7, 11]. Various levels of formalisms exist to model carrier flow relationships, computer-aided functional design, and form derivation from functional description [37].

Early function vocabularies include a two-level hierarchy of Motion, Power, Enclose, and Control functions [38] and the set of 46 functions discovered through forensic study of failed army helicopters [39]. Another representation is the multi-level flow model [40], which includes a vocabulary of six material and energy processes, four actions, and three relations, in order to model large systems. A major and popularly used vocabulary is the Functional Basis (FB) [6], which was developed by empirical dissection of electro-mechanical products' functions and flows through reverse engineering. The functions and flows were catalogued, until no new terms were necessary to describe subsequent products. The resulting vocabulary was reconciled later with a similar effort at the National Institute of Standards and Technology [41] to form a reconciled vocabulary [42] containing 53 verbs for modelling the functions and 45 nouns for the flows, organized into a three-level taxonomy.

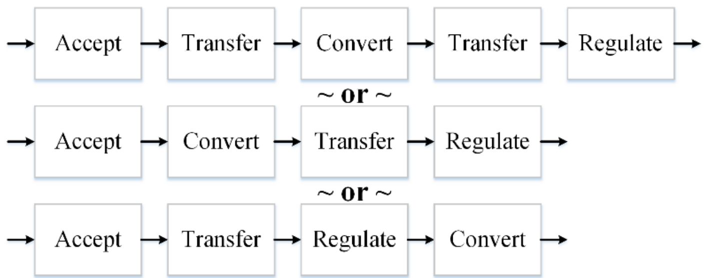

Figure 2. An example of 3 equivalent functional models of a common AC/DC adaptor plug with an on/off switch.

The Design Repository at Oregon State University (OSU) [11, 43, 44] is an online archive of design information of a wide variety of products, obtained through systematic reverse engineering. It contains data about components, functions, and other aspects of the products. It is currently used to support multiple research projects and contains information about 184 products and 6906 unique parts. The function models in the Design Repository are created using the FB as the language. Although there were initial attempts to create grammars [35] to accompany the FB, formal grammars have not been developed for that purpose. The FB and the Design Repository have been remarkable assets for design research over the past several decades; many of the reasoning systems, tools, and methods mentioned above under the Engineering Design section are based on the FB vocabulary and the Design Repository as a source of function models. Notably, the development of the FB, especially its convergence into a finite set of terms and reconciliation with other designers and other vocabularies [41], is testimony for the preference of human designers to reuse function terms in models. Yet, these human designers can construct multiple correct (based on vocabulary and grammar) yet equivalent (although not necessarily identical) functional models of the same system as shown in Figure 2. Note that neither the order the number, or even in some cases the type of functions is sufficient to uniquely establish the form of the model.

2.2. Alternative Modelling Approaches

Aside from functional modelling, other techniques have gained more extensive use in industrial practice. The Systems Modelling Language (SysML) is a widely utilized approach in systems engineering for the modelling, specification, analysis and verification of complex systems. Such systems often necessitate the modelling of hardware, software, information, personnel, and facilities. These models are represented with a set of nine different network diagrams composed of abstract blocks connected with 11 types of modelled flows. Through these graphs, the Requirements, Context, Use, Structure, Behaviour and Allocation of the system are readily modelled [45], although the different graphs may not be internally consistent.

An alternative modelling approach, known as Object-Process Methodology (OPM) derives a hierarchical set of graphs composed of entities and links which are defined using the Object-Process Language (OPL) a subset of English. OPM represents a minimal ontology modelling language emphasizing clarity and comprehension versus completeness [46]. However, it is possible to convert OPM models to SysML models.

In addition, there is a related mathematical modelling technique known as Bond Graphs (BG). Bond Graphs represent complex multi-domain systems by modelling the energy and power flows through the system as defined by effort and flow variables. These efforts and flows define a graph, connected by nodes which enforce mathematical relations upon their connecting flows. Through the application of specific rules, it is possible to derive a mathematical expression of the behaviour of the system. [47]

Notably, each of these approaches are constructed upon a graph substructure and all of these approaches employ a limited vocabulary (describing vertex and edge behaviours) and a syntax of rules which define the relationships between vertices and edges and the validity of the graph construction. As such, the construction of these abstract system models may be modelled as a Probabilistic Network Structure.

2.3. Implications for Creativity in Engineering Design

Treffinger et al. [48] reviewed over 100 studies on engineering design creativity and proposed a framework of four cognitive processes that support creativity in engineering design. These processes include: 1) Divergent thinking (idea generation), 2) Convergent thinking (idea development), 3) Application of specific personal characteristics (a willingness to explore new ideas), and 4) Reflection (a consideration of the effects of their choices) [48, 49]. Functional Modelling can embody many of these cognitive processes. Generating a model itself is an exercise in convergent thinking, but recognizing that you could generate the model in a different (but equivalent) representation is an exercise in both divergent thinking and requires the application of specific personal characteristics. And once multiple models exist, reflection upon the implications of the differences is virtually inevitable.

Divergence in models suggests an underlying diversity in perspective of the individual members of the design team. Often this diversity of perspective offers an advantage to the design team over a more heterogenous group in divergent thinking processes [50]. However, this same diversity, may hamper convergent thinking processes if it is not recognized and understood by the design team []. Convergent thinking is also important for a design team to successfully develop a shared understanding of the design solution so that a creative design can be adopted by the team [51]. The knowledge creation necessary to create a shared understanding amongst the team members is a significant factor in the performance of new products [52].

3. Pilot Study Theory and Methodology

Our initial goal with this pilot study is to begin to answer a couple of questions:

- Q1) Do different modellers show correlations between different models?
- Q2) Do individual modellers show similar modelling patterns between models of different systems?
- Q3) Do individual modellers show even more similar modelling patterns between models of more similar systems?
- Q4) Can overall profiles of modeller behaviour predict model construction?
- Q5) Are these patterns consistent at different abstraction levels?

Ultimately, it will take additional research to fully answer these questions, but initially the goal is to determine if further research is warranted.

A functional model can be thought of as a graph, composed of vertices and edges. As shown in Figure 3, a general form of this graph would involve every vertex (denoted with circles in Figure 3) leading to a set of every possible function in the functional vocabulary, with each of the possible edges (denoted with arrows in Figure 3) representing a possible flow.

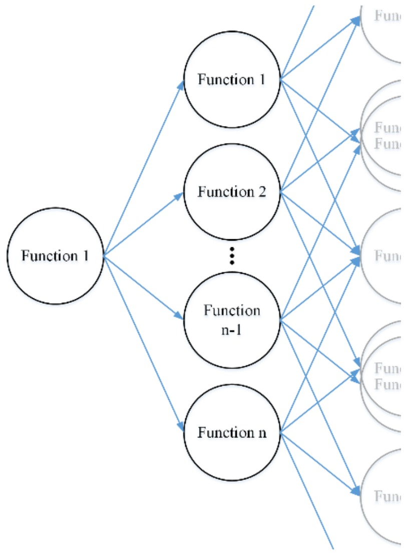

Figure 3. Conceptual Representation of the network beginning with Function 1.

The existence or nonexistence of each edge is determined by the designer. However, the state of an edge can be determined probabilistically based on the cumulative behaviour of one or more designers. We can define a state transition matrix, [S] where S_{ij} represents the probability that the edge from state i to state j exists in the model. Under the current formulation only one edge exists between any two vertices. Furthermore, the vertices in a functional model are composed of separate networks comprised of material, energy and information flows.

State Transition Matrices (STM), used to mathematically represent probabilistic network models, are used to model the functional modelling behaviours inherent within a functional model. The STM represents the probability that given a specific function, that the next function in the model is another function in the Functional Basis (FB). By analysing the correlations between the generated STMs it becomes possible to identify the differences within abstract system models which can be attributed to designer characteristics.

In our pilot study, we used two sets of functional models. The first set of models represent three products (a 3-hole punch, an emergency radio, and an iced tea brewer) which were modelled by an expert functional model user (10+ years of experience applying functional models to engineering design), and a novice user (a graduate student) recently trained in functional modelling. The resulting STMs for each model and user were generated from their models and compared via a global correlation coefficient. The second set of functional models represent four products all produced by a common group of experienced and similarly trained function modellers. These models were compared to the composite STM generated by using the other three models.

4. Pilot Study Results and Conclusions

In the first part of the study, the STMs for each functional model and designer were generated. The FB contains three levels of abstraction, the primary, secondary and tertiary levels, with the tertiary level being the least abstract. By generating the models at the tertiary level, we could further abstract the model to the secondary and primary levels. Each of these STMs were generated at the Tertiary level of the FB. In addition, a Tertiary cumulative STM representing all 3 product models generated by each designer was calculated. With the models generated, the global correlation between each resulting STM was calculated and are shown in Table 1.

Table 1. Correlations between users at the Tertiary Level of the FB.

	Novice Tertiary	Novice-Radio	Novice-Iced Tea	Novice-3-Hole Punch	Expert Tertiary	Expert-Radio	Expert-Iced Tea	Expert-3-Hole Punc
Novice Tertiary	100%	35.2%	9.5%	79.8%	0.8%	6.0%	4.1%	1.0%
Novice-Radio	35.2%	100.0%	-0.2%	-0.2%	1.6%	15.0%	-0.2%	4.1%
Novice-Iced Tea	9.5%	-0.2%	100.0%	-0.2%	2.3%	3.5%	18.1%	-0.3%
Novice-3-Hole Punch	79.8%	-0.2%	-0.2%	100.0%	-0.3%	-0.3%	-0.2%	-0.3%
Expert Tertiary	0.8%	1.6%	2.3%	-0.3%	100.0%	19.9%	43.7%	86.2%
Expert-Radio	6.0%	15.0%	3.5%	-0.3%	19.9%	100.0%	20.4%	12.7%
Expert-Iced Tea	4.1%	-0.2%	18.1%	-0.2%	43.7%	20.4%	100.0%	1.0%
Expert-3-Hole Punch	1.0%	4.1%	-0.3%	-0.3%	86.2%	12.7%	1.0%	100.0%
Novice Avg (no Self)	41.5%	11.6%	3.0%	26.5%	1.1%	6.1%	5.5%	1.1%
Expert Avg (no Self)	3.7%	6.3%	7.1%	-0.2%	49.9%	17.7%	21.7%	33.3%
Novice Avg of Avgs	20.7%				3.4%			
Expert Avg of Avgs	4.2%				30.7%			

In Table 2, we compare the STM correlations at each of the levels of the FB between the novice, the expert, and the combined novice and expert (combined) groupings.

Table 2. Correlations between users at the all Levels of the FB.

Comparisons	Correlation
Primary Level [Novice] vs [Expert]	7.0%
Secondary Level [Novice] vs [Expert]	18.7%
Tertiary Level [Novice] vs [Expert]	0.8%
Primary Level [Novice] vs [Combined]	68.0%
Secondary Level [Novice] vs [Combined]	55.7%
Tertiary Level [Novice] vs [Combined]	57.2%
Primary Level [Combined] vs [Expert]	60.4%
Secondary Level [Combined] vs [Expert]	85.8%
Tertiary Level [Combined] vs [Expert]	76.6%

In part 2, four additional tertiary level models from another common group of experienced users were compared. We selected two pairs of related products. One pair (models 1 and 2) was a coffee brewer and expresso maker, and the second pair (models 3 and 4) was a palm sander with dust collector and a hand vacuum. Additionally, combined STMs were generated, including a combined STM model that excluded each individual model in turn (i.e. All but 1 is a combined STM considering models 2, 3, and 4). Table 3 shows the resulting correlation coefficients.

Table 3. Correlations between models from a common expert group.

	All	Model 1	Model 2	Model 3	Model 4	All but 1	All but 2	All but 3	All but 4
All	100%	77%	70%	46%	45%	84%	90%	97%	96%
Model 1	77%	100%	36%	8%	8%	31%	80%	82%	82%
Model 2	70%	36%	100%	10%	6%	74%	33%	74%	75%
Model 3	46%	8%	10%	100%	38%	62%	55%	22%	39%
Model 4	45%	8%	6%	38%	100%	61%	56%	39%	19%
All but 1	84%	31%	74%	62%	61%	100%	67%	75%	74%
All but 2	90%	80%	33%	55%	56%	67%	100%	83%	82%
All but 3	97%	82%	74%	22%	39%	75%	83%	100%	94%
All but 4	96%	82%	75%	39%	19%	74%	82%	94%	100%

5. Discussion and Future Work

Reviewing the results from Tables 1, 2 and 3, we note several interesting patterns. Table 1 shows that the novice STMs tended to resemble novice STMs and expert STMs tended to resemble expert STMs (as seen by the higher correlations). Thus, we do see differences between these groups (Q1 and Q2). Furthermore, the Tertiary (cumulative) STM for each user is more predictive of each of the 3 product STMs than any single individual STM (except for the product itself). Yet, the cumulative novice STM bears very little resemblance to the cumulative expert STM. This supports the assertion that different user groups (novices vs. experts) have different modelling behaviours (Q1 and Q5).

This analysis is further supported in Table 2, where despite changes in the level of abstraction, we see low levels of correlation between the two users (Q5). However, when we generate the combined STM from the expert and novice data, we do see much higher correlations between the STMs at all levels of the FB (Q4). With a suitable sample size, it may be possible to generate an STM that can identify instances where a model deviates from the "norm" and thus a divergent perspective is being applied.

In Table 3, we further note that the pairing of related products (models 1 vs. 2 and 3 vs. 4) yields strong correlations between the STMs (Q3). We further note that the comprehensive STM (data from models 1-4) produced high correlations to all STMs and that the worst correlations were to comprehensive STM that did not include the specific functional model being compared. With only four models in the set, this is not surprising. However, the overall high correlation between the comprehensive STMs and the individual models produced is encouraging (Q4).

Based on the data from this pilot, we intend to conduct a broader study, including more participants, more models, and examining additional mechanisms to generate and compare STM representations of Functional Models.

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